SEDIMENTOLOGY OF THE DAKOTA FORMATION (CRETACEOUS), UINTA MOUNTAINS, NORTHEASTERN UTAH

by

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FINAL READING APPROVAL

To the Graduate Council of the University of Utah:

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ABSTRACT

Beds of the Dakota Formation in northeastern Utah represent a fluvial environment in which deposition occured in two basic types of streams: large meandering streams and smaller alluvial plain streams. The large meandering streams were characterized by lateral migration and point-bar deposits. These deposits are relatively thick; have high sand/shale ratios ranging from 2.3/1 to 13/1 and have laterally continuous individual channels. Also, the outcrop itself is laterally continuous over several hundred feet forming thick, unbroken exposures of sandstone. Deposition was cyclical with as many as six vertically adjacent channel deposits.

The alluvial plain streams were characterized by channel avulsion and abundant overbank material resulting in an en echelon arrangement of ancient channels. These deposits are thinner and have lower sand/shale ratios that are about 1/1. Individual channels, as well as the entire outcrop, are less extensive laterally than in the larger meandering stream deposits.

Textural parameters, especially grain size, are useful in distinquishing sandstone and siltstone originating in both types of streams and overbank areas. Petrographic differences are more limited in usefulness. The significant differences occurred in sandstone and siltstone that were deposited in different flow conditions within the large meandering stream channels. The contrasts

are in the percents of matrix and cement and in the relationship of quartz to matrix and cement. All of the Dakota channel deposits are quartz-rich and are quartzarenite, sublitharenite and subarkose.

Evaluation of paleocurrent azimuths taken from cross-stratified sedimentary structures showed that the azimuths are fairly well concentrated in the channels for both types of streams. The similarity of paleocurrent information suggests that the alluvial plain streams were also meandering. The net regional direction of sediment movement was to the north with the ultimate site of deposition possibly being west-central Wyoming.

In studying the overall dispersal system, it was found that the large meandering streams evolved through two stages of development. First, this stream system was characterized by degrading streams in disequilibrium with the surroundings. Later, (in Dakota time) this stream system reached "grade" and equilibrium with the surroundings. Both stages of stream development are registered in all outcrops of large meandering stream deposits.

A new upper contact is proposed at the base of the "coarse-grained unit". This unit is a pebbly sandstone and conglomerate heretofore included within the Dakota. It is believed, however, that this unit is genetically related to the transgressing Mowry sea, represents a transitional environment between continental and marine conditions, and was strongly affected by tidal currents. The unit is therefore considered part of the Mowry Formation.

The source area for Dakota sediment was probably the Meso-cordilleran geanticline. The composition of the source terrane was

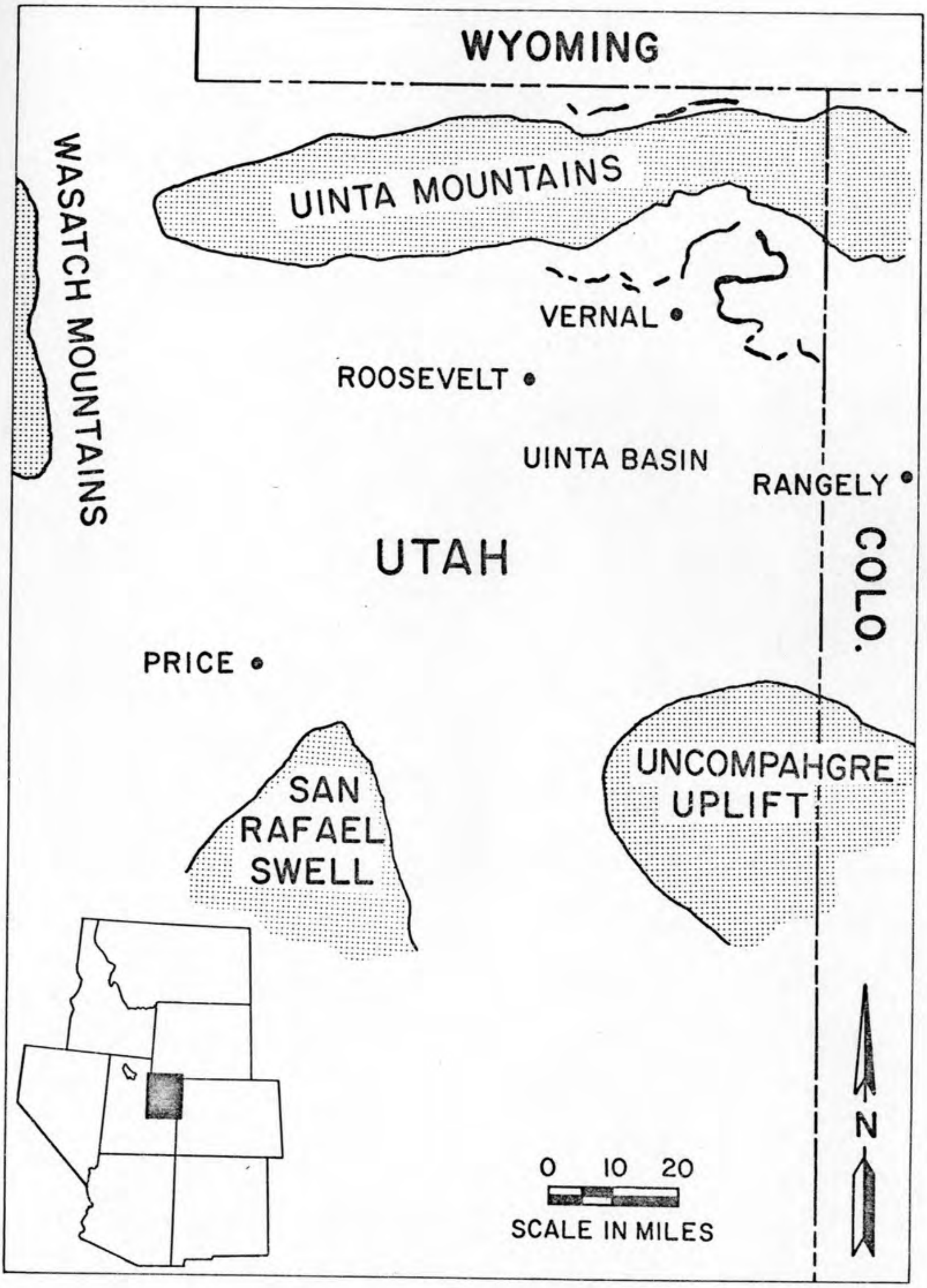
was strongly dominated by sedimentary rocks.

The environment of deposition probably was a low-lying alluvial, coastal plain. The first stage of development of the large meandering streams was farthest from the sea. The second stage and the alluvial plain streams were evidently much closer to the sea.

INTRODUCTION

The Dakota Formation in northeastern Utah is a nonmarine, continental deposit of Cretaceous age. More precise estimates of its age are very difficult to determine because of a complete lack of fossils within the formation in the study area. It has, however, been bracketed by the dated Mowry and Cedar Mountain Formations. The Dakota Formation is considered by many authors (Haun, 1959, 1963; Haverfield, 1970; Kinney, 1955; Reeside, 1923; Suttner, 1969; Walton, 1944; Weimer, 1962, 1970) as both Lower and Lower-Upper Cretaceous age.

It is the object of this thesis to determine the environment of deposition of the Dakota Formation and to evaluate that environment in a detailed manner. Knowledge of the Dakota Formation in northeastern Utah will be helpful in interpreting the geologic history of the region during the Cretaceous. It may also prove helpful in understanding some Cretaceous correlation and facies stratigraphic problems because the study area includes some of the westernmost exposures of the Dakota and, therefore, may be closest to the source area. The Dakota has been studied previously in Colorado, the Colorado Plateau of Utah and Colorado on the south, and formations probably equivalent to the Dakota in Wyoming on the north. Figure 1 is an index and outcrop map of the study area.



INDEX AND OUTCROP MAP OF DAKOTA FORMATION, UNITA MOUNTAIN AREA, UTAH

Fig. 1

GENERAL STRATIGRAPHY

Late Jurassic-Early Cretaceous stratigraphy presents some of the most complex stratigraphic problems in the western interior. This subject has been discussed by many authors with almost as many different interpretations (Burk, 1957; Cobban and Reeside, 1952; Eyer, 1969; Furer, 1970; Hale and Van De Graff, 1964; Haun, 1959; Haun and Barlow, 1962; MacKenzie and Poole, 1962; Reeside, 1944, 1955; Scott, 1970; Stokes, 1944, 1952, 1955; Young, 1960, 1970). Because it is beyond the scope of this study to make a regional interpretation of Cretaceous boundaries and facies changes, local stratigraphy within the study area was used.

The Dakota Formation is bounded above and below by the Mowry and Cedar Mountain Formations respectively. The Mowry is a dark gray to black, siliceous marine "shale". It is easily rocognized in the field by its color, fissility, diagnostic fish scales and by its slope-forming topography. Vegetation growing on the Mowry is rather sparse. The Cedar Mountain Formation, of continental origin, is also easily rocognized by its slope-forming characteristics and its variegated colors of red, purple and gray. Sediments of the Cedar Mountain Formation were not examined in detail, but cursory observations indicate that it is primarily composed of claystone and siltstone and rare sandstone lenses.

The Dakota Formation in northeastern Utah was deposited in fluvial environments. Two main facies can be recognized in the field;

a channel facies consisting of sandstone, pebbly sandstone and conglomerate and an overbank facies consisting of sandstone, siltstone and mudstone (Folk, 1968, p.27-31). This thesis is concerned primarily with the channel facies. Exposures of the channel facies are numerous and easily accessible within the study area and form resistant hogbacks or cliffs. Thickness of the channel facies is variable, but the main fluvial channel deposits are in excess of 100 feet on the south flanks of the Uinta Mountains and thicken to over 200 feet on the north flanks of the Uinta Mountains. The thickness of the formation where the channel facies is absent was not determined.

Workable exposures of the overbank facies are limited. Only one exposure of overbank sediments was measured.

Methods

Outcrops of the Dakota Formation were measured at eleven locations on the north and south flanks of the Uinta Mountains. Each section was measured with a tape and brunton compass. Detailed descriptions of the lithology and sedimentary structures were made in the field. Special attention was given to the identification, thickness and other characteristics of the cyclicity of the channels. Samples of the outcrop were taken at appropriate intervals to check for lithologic variation in the vertical sequence. Samples were carefully noted as to which fluvial cycle they represented.

A total of 353 paleocurrent azimuths were taken over the entire study area. They were evaluated at three different interpretative levels. Paleocurrent azimuths were grouped into cycles at each measured section to determine the variability of flow directions through time. Secondly, the azimuths were totaled to determine the average paleoflow directions through Dakota time for each outcrop. Thirdly, a grand total of all azimuths in the study area was evaluated to determine the average paleoslope direction of the study area throughout Dakota deposition.

Thin sections of 50 samples were studied in detail. Thirty-five of these were analyzed by modal analysis. Two hundred points were counted per thin-section. Each modal analysis was made under high magnification (x 320) with a manually operated mechanical stage.

One hundred-fifty rock samples were examined under a binocular microscope. The object of this examination was to determine the modal grain size, frosting, sorting, color and roundness of sand-sized detrital grains.

Sixteen samples were selected for X-ray analysis. Some of the samples were prepared to determine the bulk mineralogy of the channel sandstones and the overbank deposits. Other samples were prepared specifically to analyze for clay mineral content of channel sandstones and overbank deposits. All samples were run at 40KV and 20MA with Cu K-alpha X-radiation.

Because the Dakota Formation has not been dated by paleontological evidence, a special effort was made in the field and laboratory to find fossils. No fossil remains of any kind were observed in the field. Thin-section work produced no fossils indigenous to the Dakota Formation. Two samples of overbank deposits and one of a possible paludal environment that seemed likely to produce microfossils were selected for further observation. Each sample was disintegrated by treating with kerosene and water. Their examination under a binocular microscope showed no microfossils.

STRATIGRAPHY OF THE DAKOTA FORMATION

Various internal stratigraphic features are diagnostic of the Dakota Formation. These may be helpful in recognition of the formation and in understanding the environment of deposition and paleotopography. Two east-west cross-sections (figure 3 and 4) on each side of the Uinta Mountains and a north-south cross-section (figure 5) across the mountains summarize the stratigraphic features within the Dakota. Figure 2 is a regional map showing the location of the cross-sections in the study area.

Types of Outcrops

Sedimentary deposits on the flanks of the Uinta Mountains are tilted almost vertical and can be traced in a general east-west direction for many miles. The Dakota conforms to that regional outcrop pattern. Locally, however, the Dakota has three exclusive types of outcrops. Two are of the channel facies and one of the overbank facies.

Channel Facies Outcrops.--The two types of channel facies outcrops differ in thickness, sand/shale ratio, and lateral continuity of individual channels and the outcrop itself. These differences are caused by variation of stream characteristics. Some of the channel facies outcrops represent deposition in large meandering streams. These sandstones form the thickest exposures of

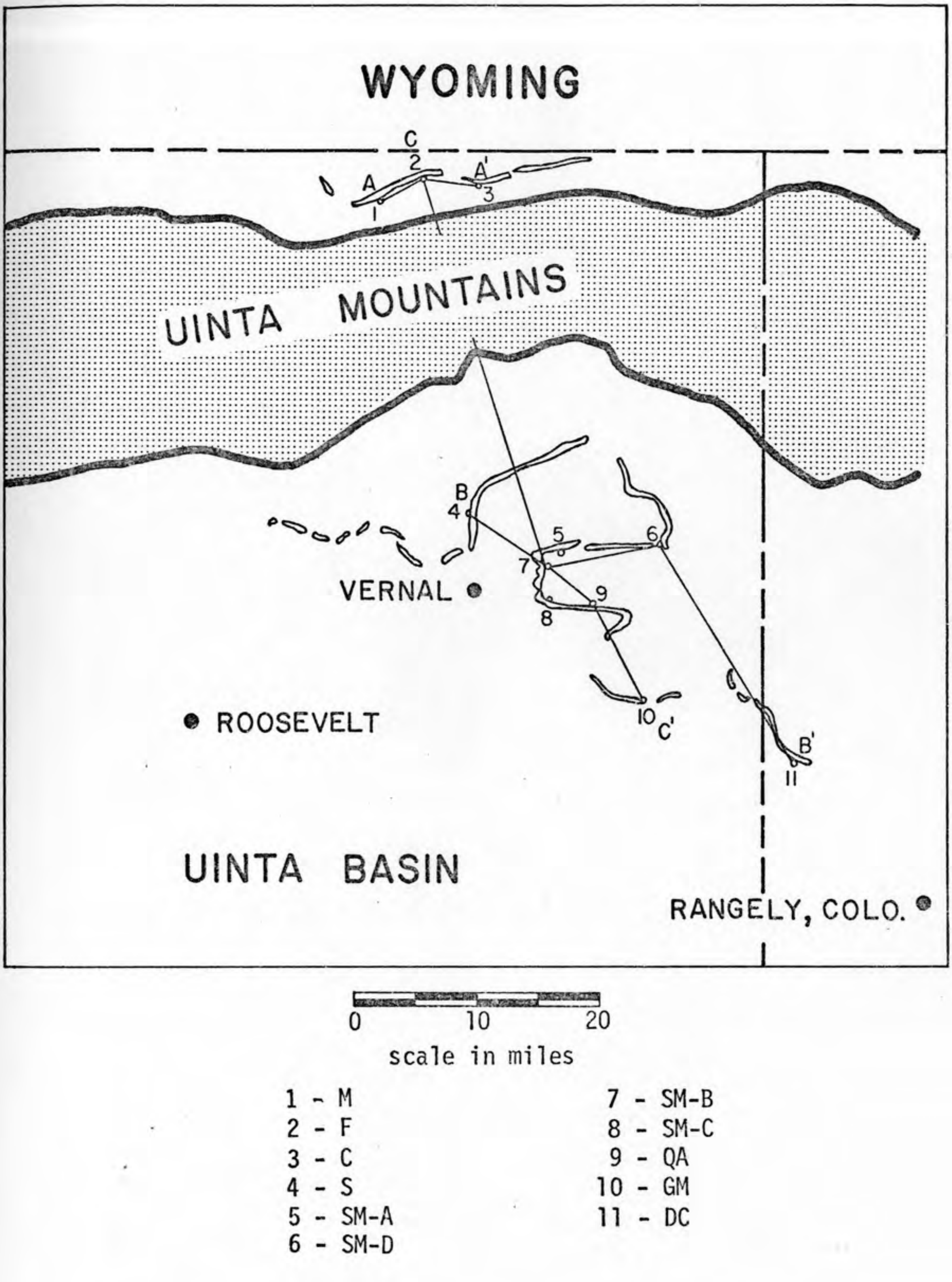


Fig. 2 -- Location of cross-sections in study area

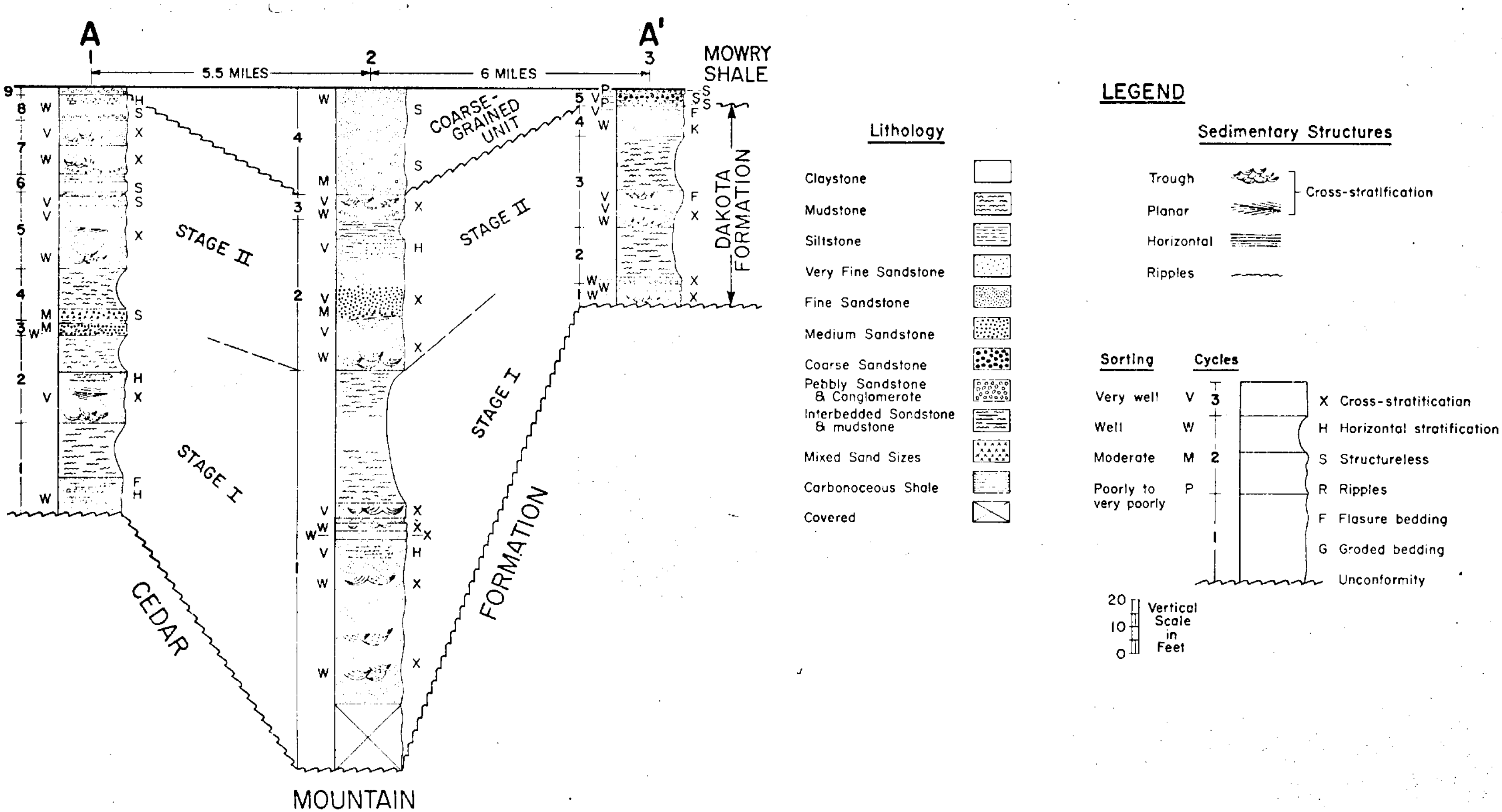


Fig. 3 -- East-west cross-section on north flank of Uinta Mountains

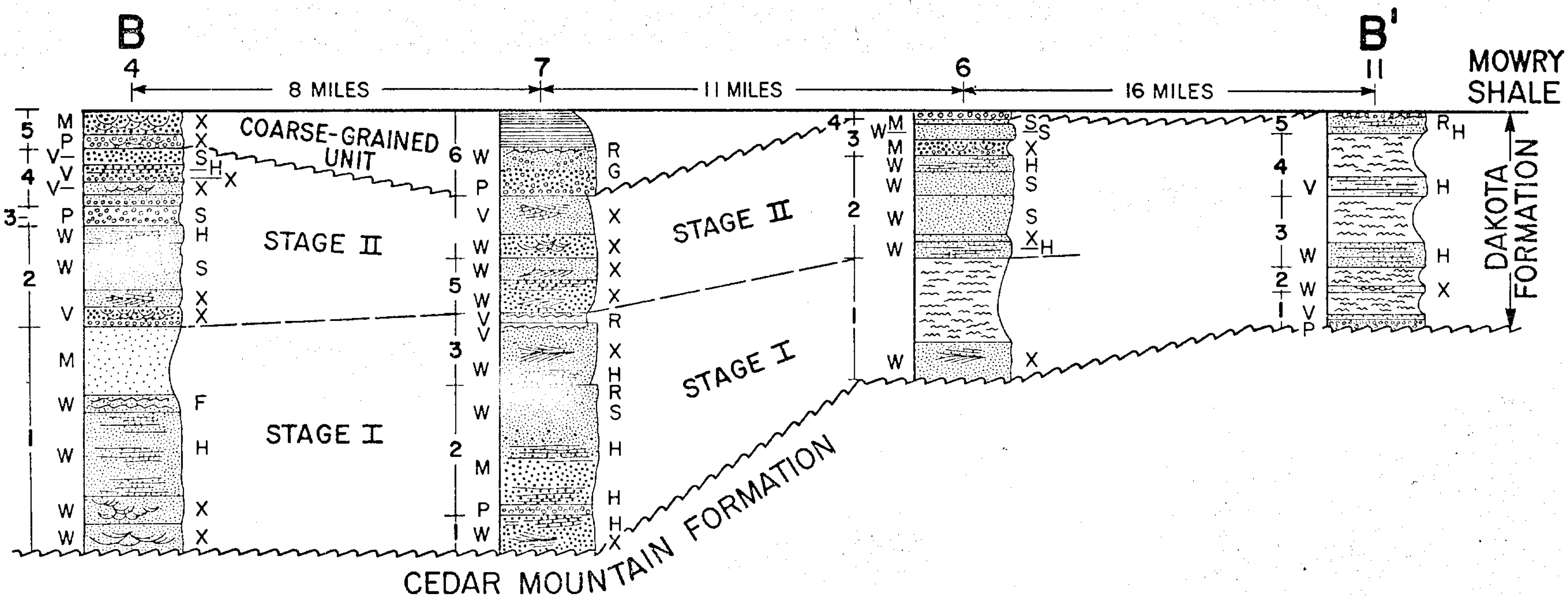


Fig. 4 -- East-west cross-section on south flank of Uinta Mountains

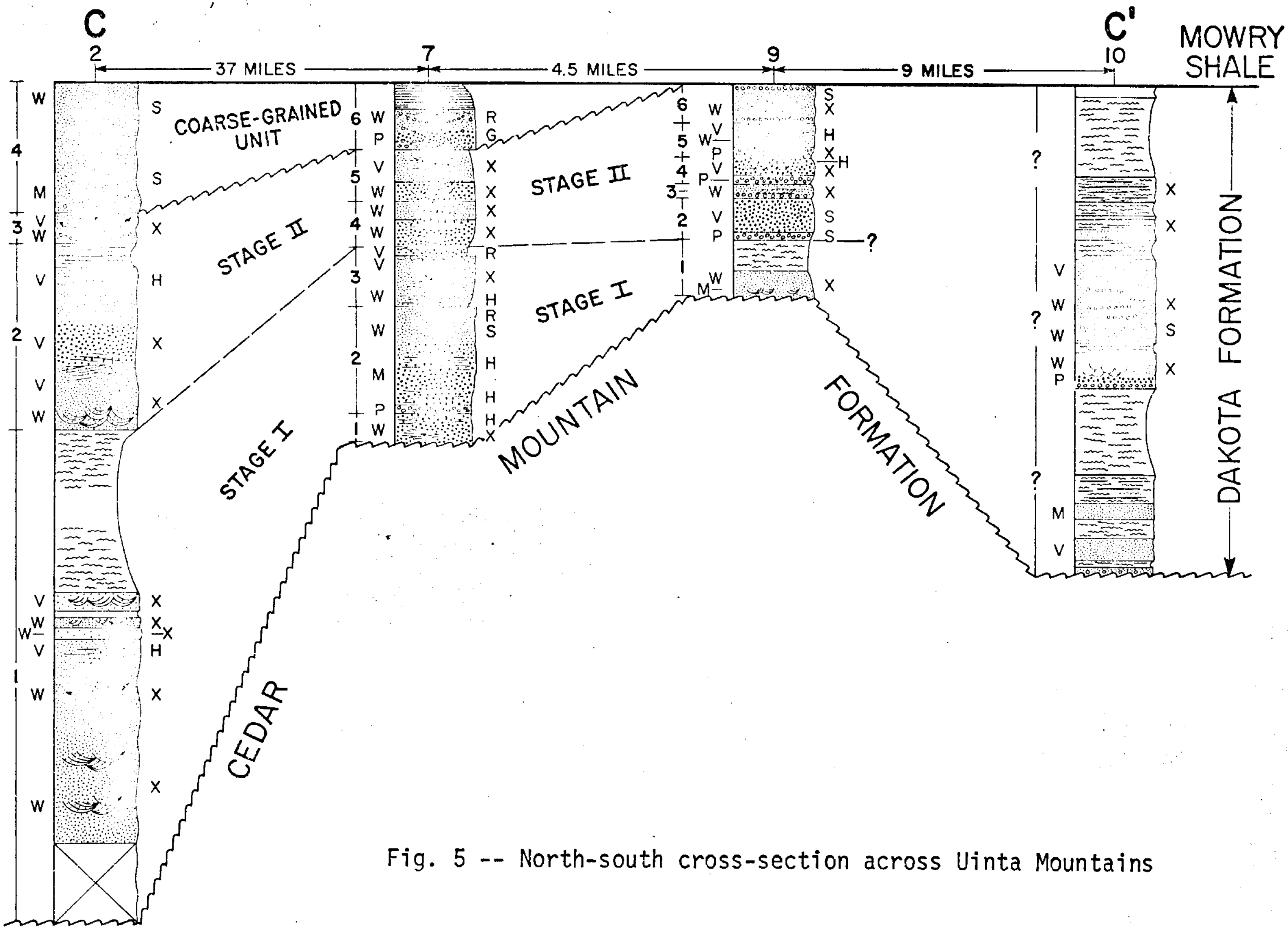


Fig. 5 -- North-south cross-section across Uinta Mountains

the Dakota in the study area. The section at Finch Draw, for example, is approximately 250 feet thick, section SM-B is 112 feet thick, and at Steinaker Draw the Dakota is also 112 feet thick. Other sections were also deposited in the same type of fluvial system, but are not as thick. Recognition of meandering stream deposits will be discussed under the heading of fluvial channels. These sandstones also have a high sand/shale ratio compared to the other channel deposits, ranging from 2.3/1 to 13/1 (figure 6). Many fluvial channels can be traced several hundred feet with little change in channel thickness. No channels were observed that completely pinch out within the outcrop. The outcrop itself is also laterally continuous, forming thick, unbroken exposures several hundred feet long. The sections at Finch Draw, Steinaker Draw and SM-B are all well over 1000 feet long.

The other type of channel facies outcrop was formed by smaller streams (figure 7). The exact nature of the stream characteristics, however, is still somewhat in question. These streams probably represent deposition on an alluvial coastal plain (Allen, 1965) with the sea to the north. The outcrop morphology of these smaller stream channels is decidedly different from that of the larger channels. This suggests substantial changes in the stream system. The thickness of these deposits are less than those of the other stream system. The section at Cholecherry Draw is 82 feet thick and the Dinosaur, Colorado section is 53.5 feet thick. The sand/shale ratio for these two sections are 1.1/1 and 1/1.5 respectively, which is less than the previously mentioned meandering channel system. Individual channels are much less extensive laterally than those of the former

Fig. 6 --Outcrop of large meandering stream deposit (section SM-B) showing cyclic deposition of fluvial channels. Outcrop thickness about 112 feet.

Fig. 7 --Outcrop of alluvial plain stream deposit (section M) showing low sand/shale ratio, pinching out of channels and crevasse-splay deposits.

stream system. Channels may or may not have the same lateral dimensions as the outcrop. Because of the low sand/shale ratio, those channels that do pinch out within an outcrop are completely surrounded by fine-grained overbank material. Very few small channel deposits, if any, are in direct contact with one another. Virtually all are separated vertically by overbank material. The outcrops are also less extensive than those originating from a large meandering stream system. At Dinosaur, Colorado, the lateral exposure of such outcrops was not directly measured; however, they were roughly 200-300 feet long and separated from the next Dakota outcrop by 300-400 feet of very poorly exposed overbank material.

Overbank Facies Outcrops.--Informative outcrops of the overbank facies are rare in the study area. Because of the paucity of sandstone and the lack of channel deposits, the overbank facies is almost always a slope-former. It is usually covered with vegetation, talus or both. The overbank facies of the Dakota is therefore characterized by its slope-forming habit, and rare sandstone and lack of channel deposits. This, in effect, provides few natural exposures. A single roadcut on Highway 40, of which at least part represents the overbank facies, did allow meaningful observations to be made. It should be noted that this facies is also present in outcrops of the channel facies, but, as shown by the sand/shale ratio, it is a minor constitutent in the large meandering stream deposits and forms approximately 50 percent of the channel deposits originating on the alluvial coastal plain.

Formational Contacts

The Dakota-Cedar Mountain contact is unconformable. Relatively large Dakota streams have incised into the underlying Cedar Mountain Formation as shown by erosional channels filled with sandstone and minor conglomerate. Relief of this erosional surface is as much as 50 feet (Hansen, 1965). The magnitude of the time hiatus or the amount of sediment removed at this surface was not determined. Wherever this contact is locally exposed, it is easily recognized as an erosional unconformity. Regionally, it is considered a disconformity (Hansen and Bonilla, 1956, Hansen, 1965).

The upper contact with the Mowry Formation is probably unconformable. The contact separates a transgressive marine deposit from a continental fluvial deposit. Since the Dakota is continental, it probably represents a time of sub-aerial erosion and localized stream deposition. Therefore, it is likely that the upper contact represents an interruption of deposition for some unknown length of time. It is still not known how the sea transgressed over the shore sands. Physically, the contact is sharp above the channel facies and almost unrecognizable above the overbank facies.

FLUVIAL CHANNELS

Detailed observations of the Dakota fluvial channels were made to determine the nature of the ancient streams and understand the processes that were operative during deposition. This was achieved by examining rock types, channel thicknesses, internal structures, vertical profiles and inferred flow regimes. The texture was also studied, but is discussed under its own heading. Characteristics of single channels will be examined first, then followed by a discussion of the superposition of channels and the resulting cyclic features of the channel facies.

Rock Types

Each fluvial channel can be divided into two lithologic units. The first unit is a coarse, poorly-sorted basal sandstone or conglomerate that directly overlies the erosional surface at the bottom of the channels. Extremes in grain size range from medium-grained sandstone to pebble conglomerate. Intermediate grain size pebbly sandstone (5-30% gravel-size material) is, by far, the most common lithology found in the coarse-grained basal deposits. Whenever gravel-size material is present, either in pebbly sandstone or conglomerate, granule-sized material is more common than pebbles in the basal units. True pebble conglomerate is rare, but present. Most conglomerate is actually granule-conglomerate. The gravel-sized material is composed of chert, metamorphic rock fragments and sedimentary rock fragments. The basal deposits commonly contain boulder-size fragments of bank material. These fragments are primarly mudstone and lesser amounts of siltstone. Except for the medium-grained sandstone, the basal beds are considered to represent channel lag deposits. Wood fragments and concretions, commonly reported in other channel lag deposits, are not present in the basal units of the Dakota. Visible sedimentary structures are also absent with only one possible exception. Clay is abundant and is the primary cementing agent.

The second lithologic unit is the finer grained sandstone deposited above the channel lag deposits. Aside from grain size, this lithologic unit is characterized by abundant sedimentary structures, sorting, color and the friable nature of the sandstone in the outcrop. This unit forms as much as 95 percent of the thickness of the larger channel deposits and lesser percentages of the smaller channels. Grain size ranges from silt to coarse-grained sand, but siltstone (Folk, 1968, p. 27-31) and coarse-grained sandstone are rare. Sandstone of intermediate grain size is the most common and fine-grained sandstone is dominant. Gravel-sized material is rare to absent. Where present, gravel forms isolated granules randomly distributed in the sandstone or pebbly stringers in the sandstone.

Channel Thicknesses

The thicknesses of separate channels were measured to obtain some idea of the size of the Dakota streams and to see if channel correlations could be made within the study area. Measurements of only fully exposed channels were used. The thicknesses of overbank deposits were excluded when present in channel facies.

The histogram (figure 8) shows the percent of channel deposits plotted against thickness. Almost 80 percent of all individual channel deposits are less than 20 feet thick. The remaining 20 percent range from 20 feet thick to over 40 feet thick. This suggests that during Dakota time there was wide variation in the size, and probably morphology as well, of the streams.

Channel thicknesses from the two different types of channel facies outcrops were compared. A total of 22 fully exposed channels associated with the main meandering stream systems were measured. Their thicknesses plot in all 5 catagories of the histogram. Seventy-three percent are 20 feet thick or less. The remaining 27 percent are 20 feet thick or more. Nine percent of the 22 channels are 40 feet or more in thickness.

Seven fully exposed channels were measured from channel facies outcrops that possibly originated on alluvial coastal plains. Their channel deposits are much more restricted in thickness. Five of the seven channels (71.5%) are less than 10 feet thick. The remaining two are between 10 and 20 feet thick. Only two channels (29.5%) plot in the second bar (10-19.9 feet).

Correlation of channels by comparing measured sections was attempted but proved to be unsuccessful. The channels that appear most likely to be correlated are the largest channels that are in close proximity to one another. The basal channels at Steinaker Draw and at section SM-B are such a possibility. This noticable lack of correlation is indicative of the temporal nature of streams.

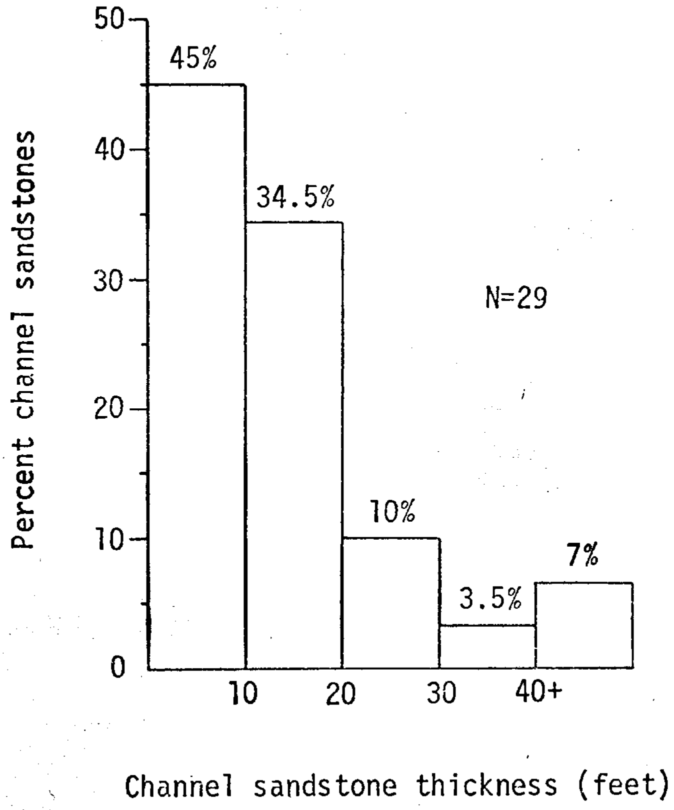


Fig. 8 -- Histogram showing frequency of channel thicknesses

Sedimentary Structures

Sedimentary structures are abundant in the Dakota Formation. Detailed studies of the various structures made possible the interpretation of the general environment of deposition, the nature of the Dakota streams, the dispersal system present during deposition, and the direction of possible source areas.

Cross-stratification.--The most common types of primary sedimentary structures observed in the field are trough and planar cross-stratification. Trough structures are produced by scouring action and subsequent in-filling. Sets of trough cross-strata range in thickness from less than two centimeters to slightly more than one meter. Based on the McKee and Weir (1953) classification, all troughs are small- and medium-scale. Planer cross-stratification is probably the product of migrating sand waves (McDowell, 1960). As with troughs, planar cross-stratification is small- and medium-scale. Only one example of simple cross-stratification was observed.

Inclined forset beds are abundant. Two types are recognized, tangential and avalanche. Avalanche forsets suggest a greater rate of deposition than tangential forsets. Forset beds range in height from inches to several feet. One example, a few hundred feet north of measured section SM-B, has a set of inclined forset beds with essentially horizontal boundary surfaces that are 10 feet apart.

Horizontal Stratification.--The number of occurrences of horizontal stratification in the Dakota is subordinate only to the cross-stratified structures. The occurrence of this type of stratification, in terms of its stratigraphic position within channel deposits, suggests that it is sensitive to flow conditions. For example, where the vertical sequence of structures can be observed and the lateral exposure is not extensive, horizontal stratification is usually present in the upper portion of channel sequences. When exposures are observed laterally, away from the main channel, horizontal stratification is often the dominant structure as the channel deposits thin. Horizontal stratification in the Dakota tends to preferentially develop in higher stratigraphic portion of the fluvial channels. This relationship indicates that in the ancient Dakota channels, horizontal stratification formed in a relatively narrow range of hydrodynamic parameters. Variation in the position of horizontal stratification does exist, but abundant field observations indicate that the position of this type of stratification is reasonably consistent.

Thicknesses of bedding planes range from a minimum of .0625 inches to a maximum of 1.5 inches. The majority are laminations (McKee and Weir, 1953). Thicknesses of sets vary from less than 1 foot to 21.5 feet. The length of horizontal stratification also varies from less than 1 foot to more than 20 feet. Based on the McKee and Weir (1953) classification, small-, medium- and large-scale examples are present. It should be noted that small-scale examples are rare, and medium- and large-scale examples are common.

Bedding Plane Features.--Bedding plane features include primary current lineation marks, sole marks, and rib-and- furrow structure.

Current lineation marks are the most abundant and are associated with horizontal stratification. Sole marks and rib-and-furrow structures were observed in only one locality. The sole marks were found under a ledge in a pebble conglomerate where underlying shale beds had been eroded away. The rib-and-furrow structure was found on a piece of Dakota float.

Ripple Marks and Ripple Cross-Lamination.--Asymmetric ripple marks are rare in the Dakota, but are present in the upper portions of some channels. A few small-scale, asymmetric, current-formed ripple marks were found in fine-grained fluvial sandstone. Likewise, two exceptionally good exposures of well developed linquoid ripples were found at the top of channels at section SM-B. In addition to ripple marks as a bedding plane feature, ripple cross-lamination, or flaser bedding, is also present in the upper portions of some fluvial channels. Occurrences of flaser bedding are more common than ripple marks.

Other Types.--Several other types of sedimentary structures were also recognized. They include biogenetic features (worm tracks), skrinkage cracks, disturbed bedding, overturned beds and massive beds. All but the massive and overturned beds are rare. The massive beds constitute sizable portions of a few channels. They were termed massive if structures were invisible or too faint to be recognized. Probably most of these beds contain some type of structure, probably planar cross-stratification or horizontal stratification.

Vertical Structure Profile

Dakota channel deposits show a recurring sequence of sedimentary structures (figure 9). Ascending upward from the base of the channels, this sequence begins with channel lag deposits, which usually have no structure. Above the channel lag deposits, in ascending order, are trough cross-stratification, planar cross-stratification, horizontal lamination and ripple cross-lamination (not always present). This sequence compares well with studies of point bar sequences by Bernard and Major (1963) and Visher (1965). This interpretation is strengthened with studies by Allen, 1964, 1965, 1970; Allen and Friend, 1968; Frazier and Osanik, 1961; Friend, 1965; Harms, 1963.

Channels of possible alluvial coastal plain deposition do not fit this scheme as well as deposits of large meandering streams. The main difference is that trough cross-stratification is less abundant in the former case. A more common sequence, as numbered in figure 9, is 5-3-2-1. Whatever the sequence is, however, ascending structures always indicate a decrease in flow intensity. As already indicated, no two channels are exactly alike, which reflects the variability of the basic stream parameters of channel depth, width, and flow velocity.

The thicknesses of sets of sedimentary structures (McKee and Weir, 1953) were observed qualitatively throughout the study area. Ascending sets of trough and planar cross-stratification decrease in thickness within a single channel. Horizontal stratification is less consistent. At one particularily well exposed channel at

GENERALIZED POINT BAR SEQUENCES

BERNARD & MAJOR (1963)	VISHER (1965)	DAKOTA FORMATION - N. E. UTAH
1. Small ripple cross-stratification (or small-scale)	1. Ripple cross-stratification zone	1. Ripple cross-stratification
2. Horizontal lamination	2. Horizontal laminated zone fine sand & silt	2. Horizontal lamination
3. Giant ripple cross-stratification (or medium-scale)	3. Festoon or planer strati	3. Planar cross-stratification
4. Poor bedding	3. Festoon or planar stratification; well sorted	4. Trough cross-stratification
	4. Basal zone; poorly stratified	5. Basal zone; poorly sorted; red color

Fig. 9

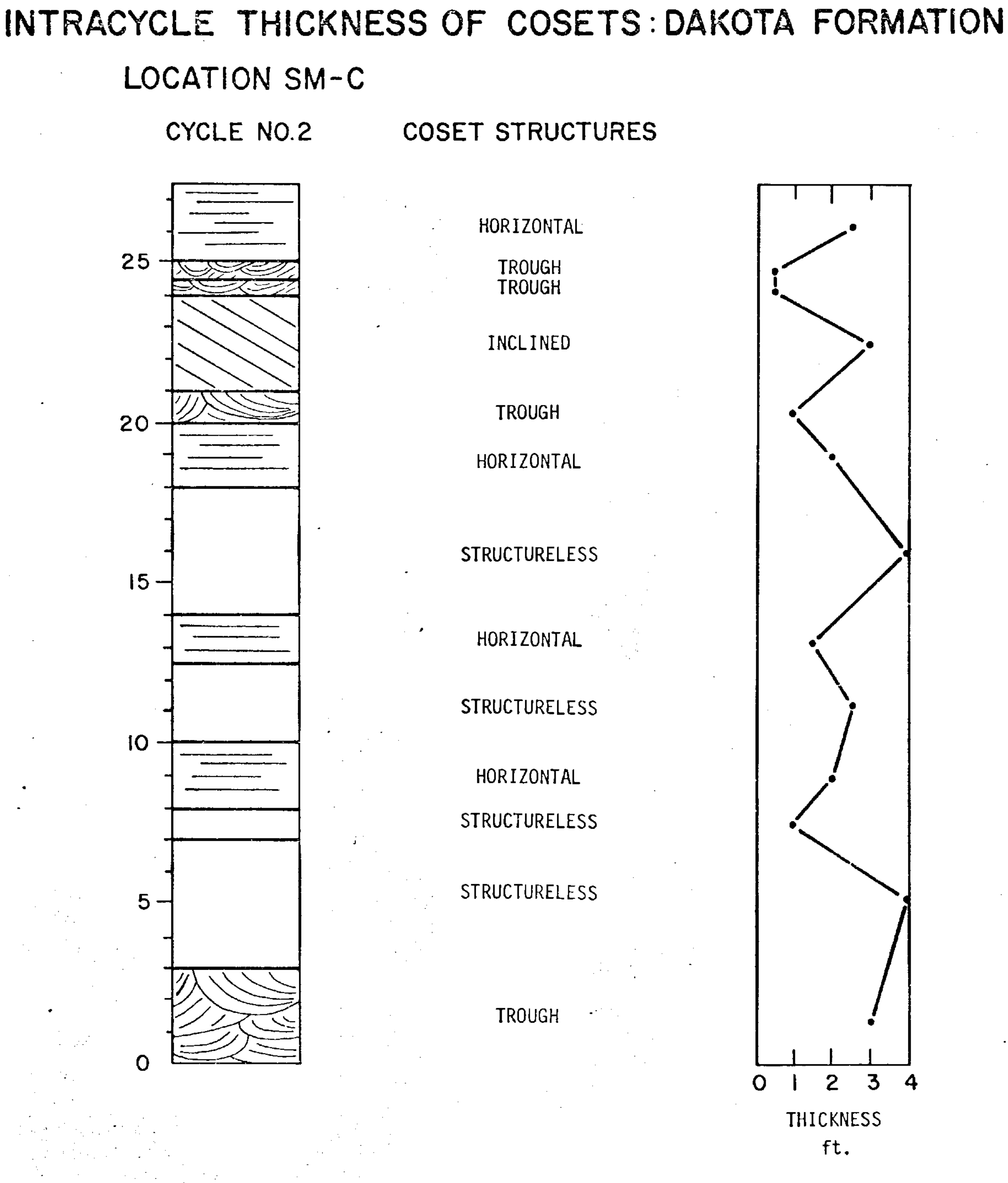

INTRACYCLE THICKNESS OF COSETS: DAKOTA FORMATION
LOCATION SM-C
CYCLE NO.2
COSET STRUCTURES
25
20
15
10
5
0
HORIZONTAL
TROUGH
TROUGH
INCLINED
TROUGH
HORIZONTAL
STRUCTURELESS
HORIZONTAL
STRUCTURELESS
HORIZONTAL
STRUCTURELESS
STRUCTURELESS
TROUGH
0
1
2
3
4
THICKNESS
ft.

Fig. 10

SM-C, the thicknesses of cosets were examined and checked for a vertical trend. As seen from figure 10, the cosets thin upward as do the sets.

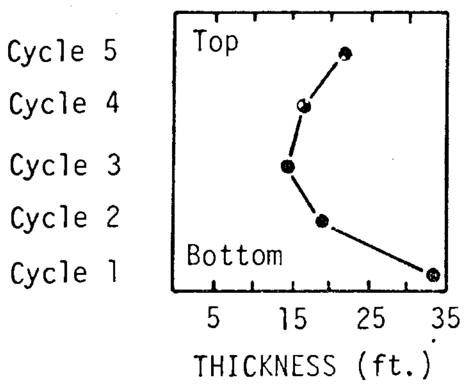
Fluvial Cycles

One of the diagnostic features of the channel facies is the repetition of beds indicating episodes of fluvial deposition. This imparts a cyclic nature to channel facies outcrops. It is convenient, therefore, to describe such deposition in terms of cycles. Each cycle represents a dingle episode of fluvial deposition, and is bounded above and below by a surface of erosion between which sediments were continuously deposited. A cycly can be composed of only channel deposits. Such cycles are diagnostic of channel facies outcrops that have high sand/shale ratios. Cycles can also have both channel and overbank deposits, a characteristic of outcrops with low sand/shale ratios (Allen, 1964; Allen and Friend, 1968).

Cycle Thicknesses.--Cycle thicknesses were measured and plotted on graphs (figure 11). Thicknesses include both channel facies and overbank facies where present. Only cycles in which upper and lower boundaries were observed were utilized in the plots. Figure 11 shows the results of cycle measurements for three channel facies outcrops with high sand/shale ratios. In each case the thickest cycle is at the base of the outcrop. Proceeding upwards, the cycles decrease in thickness, reach a minimum, and then increase in thickness. Cycle thicknesses in channel facies outcrops of low sand/shale ratio do not show a consistent pattern. However, investigation of more

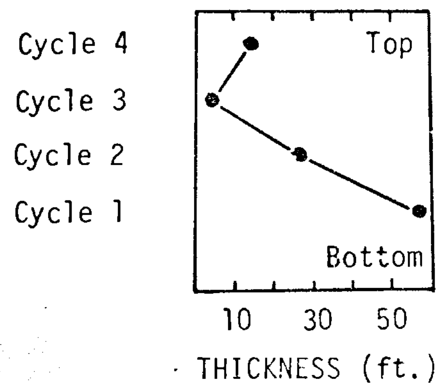
THICKNESSES OF CHANNEL CYCLES : DAKOTA FORMATION

Location: Split Mtn
Section B



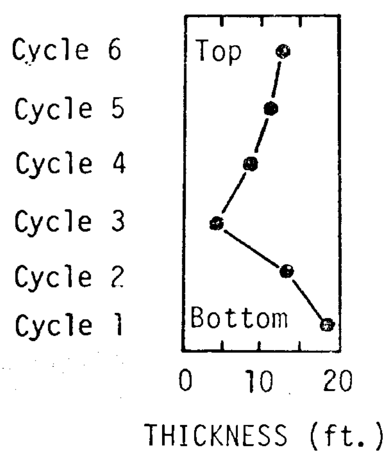
Total Thickness = 102 ft.

Location: Steinaker Draw



Total Thickness = 102 ft.

Location: Dinosaur Natl. Mon. Quarry Area



Total Thickness = 67.5 ft.

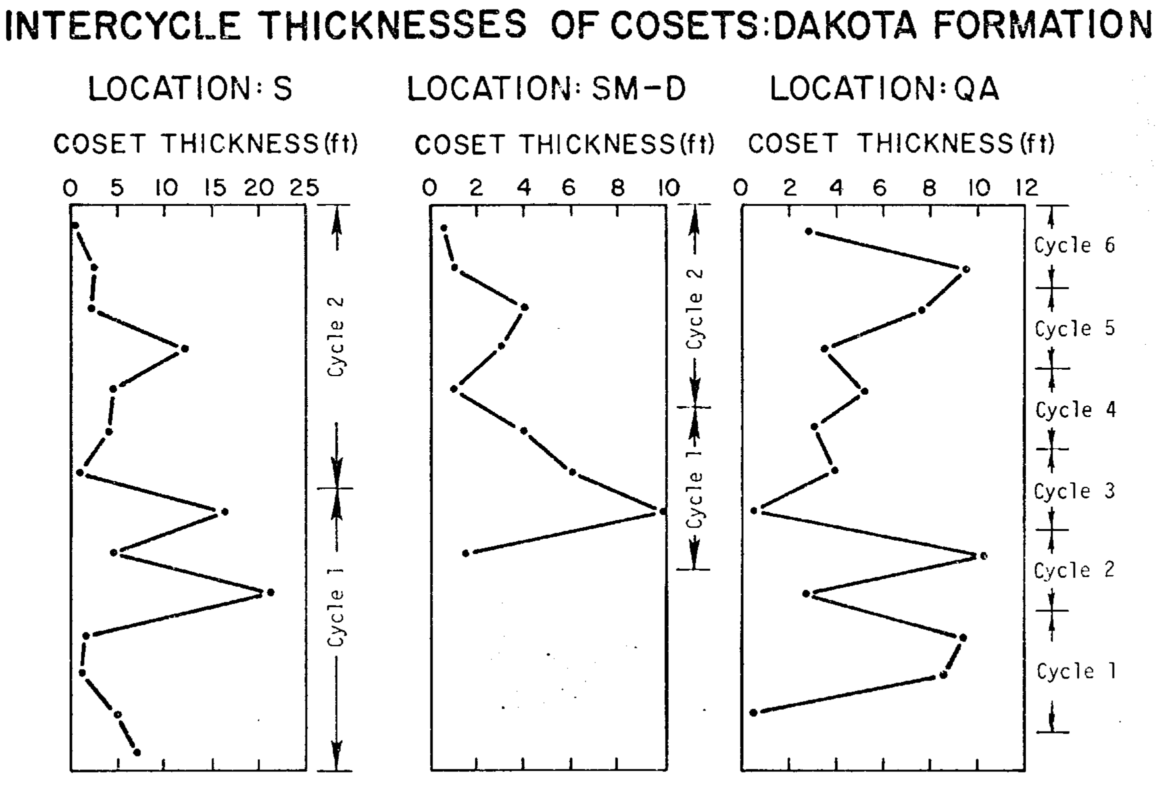
Fig. 11

exposures is needed to confirm this observation.

Intercycle Coset Thicknesses.--Coset thicknesses within vertically adjacent cycles were measured to examine thickness trends across cycle boundaries and to determine the relationship between coset thicknesses and corresponding cycle thicknesses. Sections at Steinaker Draw (S) and one on the northside of Split Mountain (SM-D) show coset thicknesses that decrease upwards both within their respective cycles and across the cycle boundaries as well (figure 12). At section QA, however, no such pattern exists.

In addition to the determination of individual coset thicknesses, the mean coset thickness within each cycle was also determined and compared to its cycle thickness. This comparison of mean coset thicknesses and cycle thicknesses was found to be essentially a direct relationship, which suggests that as the stream channels decrease in size the structures within the channel deposits also decrease proportionally in size. Although not so obvious, this same relationship exists for section QA. Cycle 3 is the thinnest cycle and also has the least mean coset thickness. Thicker cycles, such as 1, 2, 5 and 6, have larger mean coset thicknesses.

Weathering.--A distinctive weathering pattern is useful for recognizing upper and lower boundaries of cycles. This is especially helpful in studying outcrops that have little or no overbank facies. The channel lag deposits at the base of each cycle are not as resistant to weathering as the finer grained sandstone and commonly form conspicuous ledges or indentations in outcrops,



Mean coset thickness

cycle 2 = 3.7 ft.

cycle 1 = 8.1 ft.

Mean coset thickness

cycle 2 = 1.9 ft.

cycle 1 = 5.3 ft.

Mean coset thickness

cycle 6 = 6.0 ft.

cycle 5 = 5.5 ft.

cycle 4 = 4.0 ft.

cycle 3 = 2.5 ft.

cycle 2 = 6.5 ft.

cycle 1 = 6.1 ft.

Fig. 12

thereby, marking the vertical limits of each cycle. Rarely, channel lag deposits are absent and other methods of describing boundary locations were used. One of these mehtods involved color changes.

Color.--Color changes in the channel sandstone frequently are cyclic. The easily weathered channel lag deposits generally are reddish-brown. The sandstone above the channel lag deposits is white, buff and light brown. White sandstone, when present, is always found at the top of channels and is, therefore, helpful in delimiting the upper boundaries of cycles. The white coloration is related to large amounts of clay matrix (25%). Also, white sandstone weathers to smooth, rounded surfaces.

TEXTURE

The textural parameters grain size, sorting, grain morphology and maturity were studied to determine what textural features are characterisitic of the Dakota, to examine vertical changes in grain size, and to see if any are useful in interpreting the depositional environment.

Grain Size

A total of 150 hand samples was evaluated for grain size with the aid of a binocular microscope. Grains from each sample were compared with sand samples of known grain size and classified according to Wentworth (1922). Unimodal sandstone and siltstone accounts for 83.3 percent of all samples. Ninty-six percent of the unimodal samples ranges from very fine to medium-grained. Bimodal sandstone, siltstone, pebbly sandstone and conglomerate represent the remaining 16.7 percent of all samples.

Because of the abundance of unimodal sandstone and siltstone in the Dakota, a concentrated effort was made to determine and evaluate grain size variation of unimodal samples. Such samples are useful in this type of study because they can be rapidly classified by grain size. Where possible, samples were classified with grain size categories (table 1). Some samples, however, could not be definitely placed with grain size boundaries even though all of them are well to very well sorted. These samples were noted and placed <u>at</u>

TABLE 1: Unimodal siltstone and sandstone occurances within grain size boundaries*

	Location	Silt	Very Fine	Fine	Medium	Coarse	No. of Samples
Meandering Stream Deposits	SM-A	-	1	6	1	-	8
	SM-B	-	1	9	5	-	15
	SM-C	-	-	7	6	-	13
	SM-D	-	-	9	2	-	11
	QA	-	-	7	3	-	10
	S	-	2	7	3	-	12
	M	1	1	5	2	-	9
	F	1	1	7	1	-	10
Alluvial Plain Stream Deposits	DC	1	2	2	1	-	6
	C	-	1	2	-	1	4
Overbank Deposits	GM	-	2	4	1	-	7

*All samples well to very-well sorted

TABLE 2: Unimodal siltstone and sandstone occurances at grain size boundaries*

	Location	Silt		Very Fine		Fine		Medium		Coarse	No. of Samples
Meandering Stream Deposits	SM-A		-		-		-		-		
	SM-B		-		-		-		-		
	SM-C		-		-		-		-		
	SM-D		-		-		3		-		3
	QA		-		-		-		-		
	S		-		-		2		-		2
	M		-		-		2		-		2
	F		-		1		1		-		2
Alluvial Plain Stream Deposits	DC		-		-		1		-		1
	C		1		3		1		-		5
Overbank Deposits	GM		-		3		2		-		5

*All samples well to very-well sorted

TABLE 3: Total unimodal siltstone and sandstone grain size frequency

	Location	Silt		Very Fine		Fine		Medium		Coarse	No. of Samples
	SM-A	-	-	1	-	6	-	1	-	-	8
	SM-B	-	-	1	-	9	-	5	-	-	15
	SM-C	-	-	-	-	7	-	6	-	-	13
	SM-D	-	-	-	-	9	3	2	-	-	14
Meandering Stream Deposits	QA	-	-	-	-	7	-	3	-	-	10
	S	-	-	2	-	7	2	3	-	-	14
	M	1	-	1	-	5	2	2	-	-	11
	F	1	-	1	1	7	1	1	-	-	12
	Total	2	0	6	1	57	8	23	0	0	97
	Percent	2.0	0	6.2	1.0	58.8	8.2	23.7	0	0	
	DC	1	-	2	-	2	1	1	-	-	7
Alluvial Plain Stream Deposits	C	-	1	1	3	2	1	-	-	1	9
	Total	1	1	3	3	4	2	1	0	1	16
	Percent	6.25	6.25	18.75	18.75	25.0	12.5	6.25	0	6.25	
	GM	-	-	2	3	4	2	1	-	-	12
Overbank Deposits	Total	0	0	2	3	4	2	1	0	0	12
	Percent	0	0	16.6	25.0	33.3	16.6	8.3	0	0	

the appropriate grain size boundary (table 2). The results of tables 1 and 2 are summarized in table 3.

Samples were grouped and compared for the three types of fluvial deposits: large meandering stream deposits, alluvial plain stream deposits, and overbank deposits. The results are listed below.

Percent Samples Ranging from Fine to Medium Grain

large meandering stream deposits	90.7%
alluvial plain stream deposits	43.75%
overbank deposits	58.2%

Percent Samples Ranging from Very Fine to Fine Grain

large meandering stream deposits	66.0%
alluvial plain stream deposits	62.5%
overbank deposits	74.9%

Percent Samples Excluding Fine - Grained Samples

	greater than fine-grain	less than fine-grain
large meandering stream deposits	31.9%	9.2%
alluvial plain stream deposits	25.0%	50.0%
overbank deposits	24.9%	41.6%

Ratio of Very Fine to Medium - Grained Samples

large meandering stream deposits	1/3.8
alluvial plain stream deposits	3/1
overbank deposits	2/1

Percent Fine - Grained Samples Only

large meandering stream deposits	58.8%
alluvial plain stream deposits	25.0%
overbank deposits	33.3%

On the basis of grain size, certain comparisons apparently are useful in recognizing large meandering stream deposits as compared with alluvial plain stream deposits and overbank deposits. The latter two types, however, are similar in each comparison and, therefore, it is not possible to distinguish them from each other by grain size comparisons. The most significant grain size comparisons for differentiating large meandering stream deposits from the other two fluvial deposits are:

a. percent unimodal samples ranging from fine - to medium - grained;
b. percent unimodal samples less than fine grain size;
c. ratio of very fine to medium - grained unimodal samples;
d. percent unimodal fine - grained samples only.

Less significant grain size comparisons are:

a. percent unimodal samples ranging from very fine to fine grained;
b. percent unimodal samples greater than fine grained.

Figure 13 is a frequency profile chart of grain sizes for each of the three types. The large meandering stream deposits are characterized by a limited range of preferred grain sizes centering around fine-grained material. The alluvial plain stream deposits and overbank deposits are also dominated by fine-grained material, but less drastically so.

A vertical grain size profile chart was made of the large meandering stream deposits and compared with an idealized grain size profile chart (Selley, 1972) for meandering streams. The chart indicates the repetition of channel conditions at these locations.

The fining-upward of grain sizes within each cycle is indicative of point bar deposits in which laterial accretion was the mode of deposition. The fining-upward sequences also indicate decreasing flow intensities upward within each cycle (figure 14).

As previously noted, bimodal samples account for a small portion of the samples. Most are pebbly sandstone and conglomerate and represent channel lag deposits.

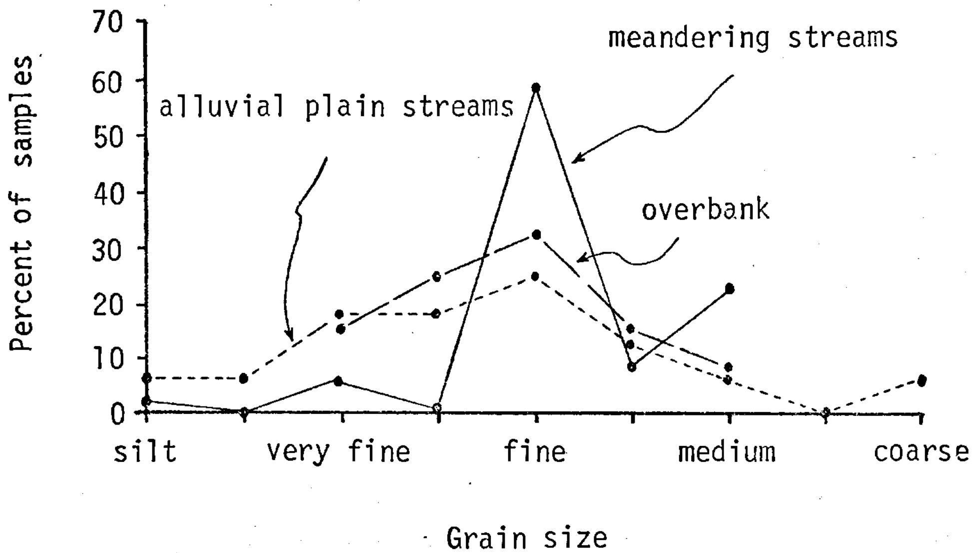


Fig. 13 -- Frequency profile chart of grain sizes

Sorting

A total of 138 sandstone and siltstone samples was examined under a binocular microscope to determine sorting. Each sample was classified by visual comparison with a sorting chart (Compton, 1962, p. 214). The degree of sorting for most samples can be readily classified. Some samples, however, apparently have intermediate

VERTICLE GRAIN SIZE PROFILE OF FLUVIAL CYCLES DAKOTA FORMATION

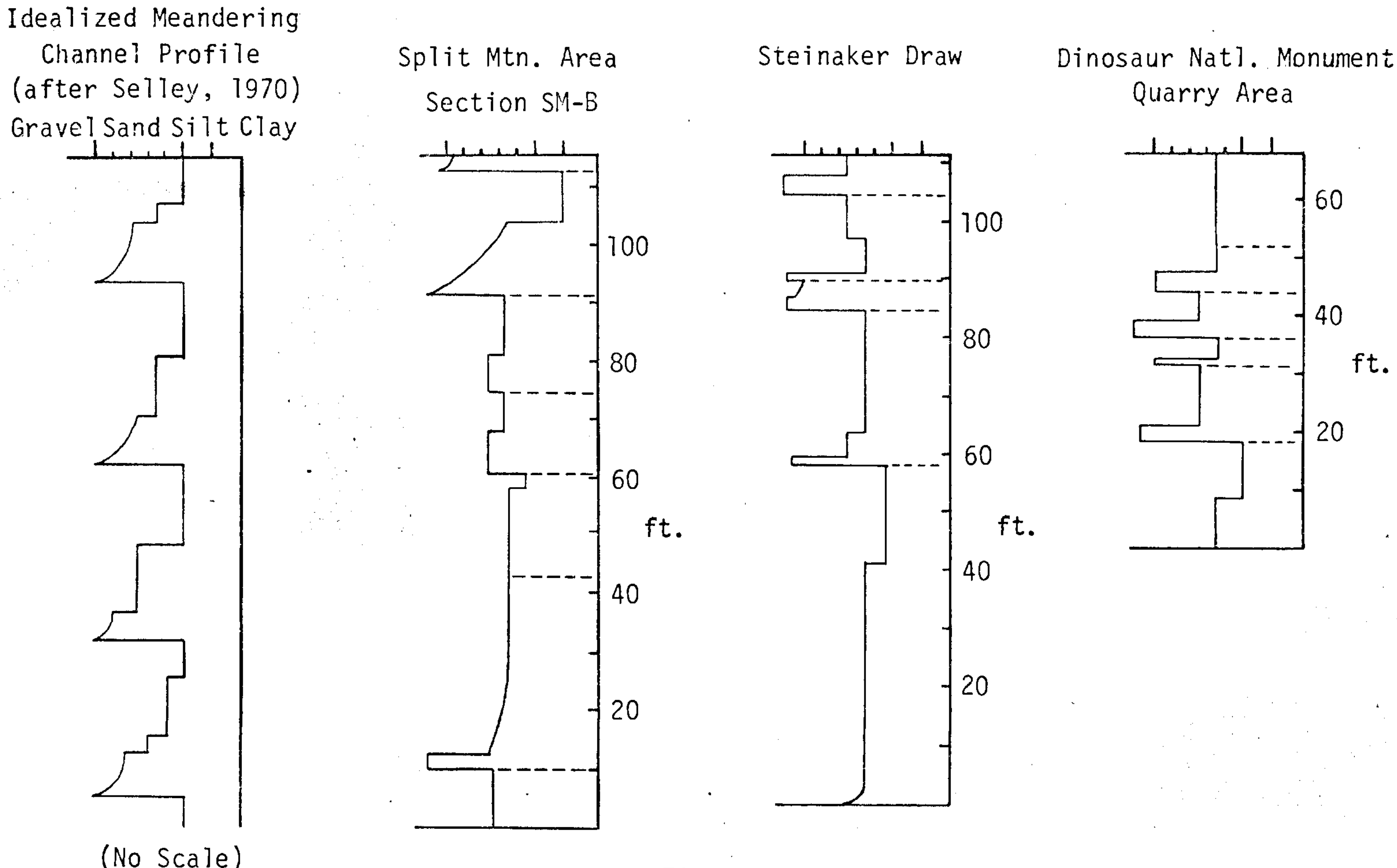


Fig. 14

degrees of sorting and are so classed. The results are presented in table 4.

Degrees of sorting ranging from well to very well are dominant and account for 81.8% of all samples. The single most common sorting category is well sorted and 39.8% of all samples fall in this class. Samples ranging from very well to well sorted plus very poorly sorted samples total 89.7% of all the samples. Instances of sorting between well and very poorly sorted material are much less common (9.4%).

Contrary to grain size, sorting does not appear to be a reliable indicator by which to differentiate the three fluvial types of deposits. Slight differences are present, such as the relatively limited ranges of degrees of sorting for alluvial plain stream samples and the dominance of very well sorted samples in overbank sandstone. These differences, however, are not considered significant because the accuracy of visual estimates of sorting is limited. Also, the magnitude and number of differences is small. Figure 15 illustrates the close similarities of the different fluvial deposits.

Grain Morphology

Roundness.--Roundness for sand and coarse silt-sized grains was determined for each sample by comparing grains to Powers' 1953 roundness scale with a binocular microscope. All samples from each location were compared and checked for a dominant natural grouping. The results are shown in figure 16. The percent values in the figure indicate the percent of the samples at that location that establish the dominant range of rounding as shown.

TABLE 4: Sorting

	Location	Very-Well		Well		Moderate		Poorly		Very Poorly	No. of Samples
Meandering Stream Deposits	SM-A	1	-	6	-	1	-	-	-	1	9
	SM-B	3	4	4	-	2	1	-	1	1	16
	SM-C	1	6	5	-	-	-	-	1	-	13
	SM-D	1	3	9	-	1	-	-	-	-	14
	QA	3	-	4	2	-	-	1	-	3	13
	S	3	2	8	-	1	-	-	-	2	16
	M	5	1	4	1	1	-	-	-	1	13
	F	5	3	3	0	0	0	0	0	0	11
	Total	22	19	43	3	6	1	1	2	8	105
	Percent	20.9	18.0	40.9	2.8	5.7	0.95	0.95	1.9	7.6	
Alluvial Plain Stream Deposits	DC	2	1	3	-	-	-	-	-	1	7
	C	3	1	5	-	-	-	-	-	1	10
	Total	5	2	8	0	0	0	0	0	2	17
	Percent	29.4	11.7	47.0	0	0	0	0	0	11.7	
Overbank Deposits	GM	5	2	4	1	2	-	-	1	1	16
	Total	5	2	4	1	2	-	-	1	1	16
	Percent	31.25	12.5	25.0	6.25	12.5	0	0	6.25	6.25	

Certain differences apparently are present between the three fluvial types. Large meandering stream deposits are dominated by grain roundnesses ranging from subangular to subrounded and 83.05% of these samples are within the range of subangular to rounded. Alluvial plain stream deposits tend to be less rounded. Locations DC and C together have 90% of their samples within the roundness range of angular to subrounded. The most distinctive suite of samples, in terms of roundness values, is the overbank samples from section GM.

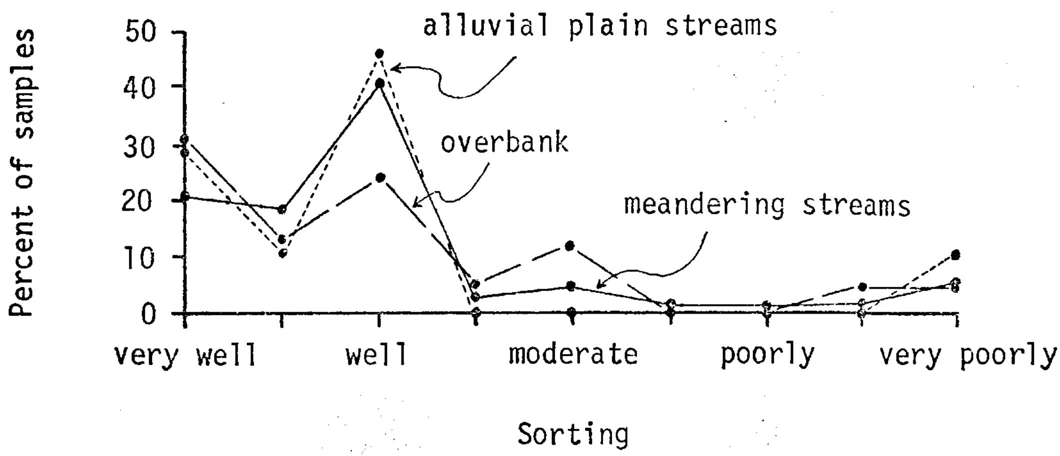


Fig. 15 -- Frequency profile chart of sorting values

Almost every sample has a wide range of roundness values relative to samples at other locations. As a result, the tendency for grains to group themselves in terms of rounding is weaker than at other locations. Of all samples at GM, 82.4% range from very angular to subrounded, a much larger range than for similar percentages in the other two types of fluvial deposits.

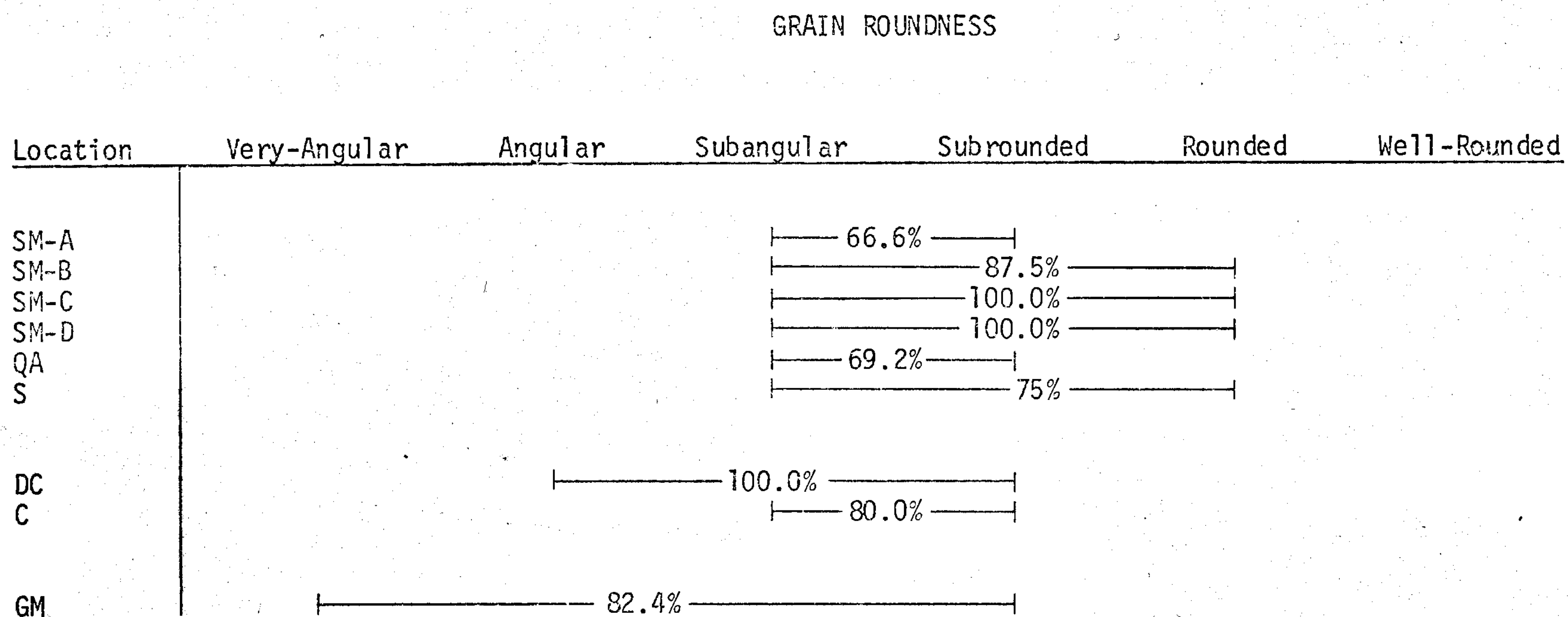


Fig. 16 -- Dominant groupings of grain roundness

Grain Surfaces.--Surface textures of quartz grains were examined under a binocular microscope. Grains from each sample were observed under high intensity light on a black background. Virtually every sample contains abundant frosted quartz grains; indeed, most samples are dominated by such grains. Although no quantitative studies were made, the larger and better rounded sand-sized grains are more often frosted than are the more angular grains at the lower limit of sand-sized material. Spot checks were made to see if the frosting was the result of coating by calcium carbonate. This involved dropping warm HCl on the grains, dissolving the carbonate, and then allowing them to dry. The results were negative in each case.

Other quartz grains are "sparkly" in appearance. These grains have flat, smooth surfaces as a result of silica overgrowths. Their occurance is limited, however, and is important at only two locations, sections GM and DC.

Textural Maturity

Fifty thin-sections were studied to determine the textural maturity of the Dakota sediments. Determinations were made according to a method prepared by Folk (1968, p. 102-103). Effects of diagenesis, such as the formation of authigenic clay minerals and quartz overgrowths, were carefully discounted. Sandstone and siltstone is dominantly mature as determined by less than 5 percent detrital clay, subangular to very angular grains, and being well sorted or better. Lesser amounts of sandstone and siltstone are submature and supermature.

Occasional textural inversions were found by examining thin-sections of channel lag deposits. These inverted samples contain rounded, poorly-sorted grains in a clay matrix. The clay material of the channel lag deposits presumably came from lateral erosion of stream banks. One other case of textural inversion is represented by an overbank sandstone at section GM. In this case, well sorted but not well rounded grains were deposited as a clay matrix. This sample also has almost no porosity. This type of inversion in the overbank setting indicates the high energy conditions associated with flooding. Ironically, other overbank material does not show textural inversion, which suggests that overbank material can be well sorted and not result solely from vertical accretion simply by the settling out of particles.

PETROGRAPHY

Thirty-five modal analyses provide information for the description and evaluation of the petrographic aspects of the Dakota. Virtually all samples required impregnation with epoxy because they are friable. All samples were stained for potassium feldspar. X-ray diffraction analysis of 16 samples made possible the mineralogical determination of the matrix. All rocks studied in thin sections were classified according to the system prepared by Folk (1968). The three end members of this classification are quartz, feldspar, and rock fragments. The quartz pole includes all quartz types except quartzite and chert. The feldspar pole includes single feldspars plus granite and gneiss fragments. All other rock fragments fall at the rock fragment pole. Matrix, therefore, consists of authigenetic clay, detrital clay materials in which definite grain boundaries are not visible, and terrigenous material less than 1/16 mm. Chemically precipitated pore-filling silica (rare), and silica overgrowths and calcite were counted as cement.

Pebbly Sandstone and Conglomerate

Mineralogically, the pebbly sandstone and conglomerate that constitutes the channel lag deposits is dominated by rock fragments, matrix and quartz grains. Both feldspar and chemical cement are minor constitutents and range from zero to one percent. These rocks are poorly to very poorly sorted and generally are reddish-brown.

This coloration is present in the matrix and in soft sedimentary rock fragments. It is apparently hematite stain emanating from sedimentary rock fragments and staining the matrix. This suite of rocks is less mature than the sandstone and siltstone because of the presence of detrital clay and labile soft sedimentary rock fragments.

Rock fragments range in grain size from sand to pebbles. All granule- and pebble-sized material are rock fragments consisting of chert, metamorphic rock fragments (MRF's), and sedimentary rock fragments (SRF's) other than chert. Chert and MRF's are subrounded to rounded. SRF's are irregular in form because of compaction. Compositionally, chert and MRF's average 17.8 and 17.9 percent respectively of the pebbly sandstone and conglomerates. SRF's average 4.2 percent. Totally, rock fragments average about 40.0 percent of the composition of these rocks.

The matrix is authigenic and detrital clay. X-ray diffraction indicates that kaolinite is the most common clay mineral. Distinction between matrix and SRF's is often difficult because of the reddish-brown stain, which sometimes is opaque. The matrix material is present within pore spaces in some samples and forms "floating grains" in others. Sand-size material is mainly quartz except for lesser amounts of rock fragments and rare grains of potassium feldspar (orthoclase). Chemically precipitated silica, in the form of quartz overgrowths and pore-filling cement, ranges from zero to 2.5 percent. Porosity ranges from zero to 13 percent. The average porosity is 4.7 percent. The principle bonding agent is the matrix. Chemically precipitated cement (silica) is only a minor bonding agent. Figure 17 is a ternary diagram of nine samples of pebbly sandstone and conglomerate, which are all litharenite.

Sandstone and Siltstone

Mineralogically, the sandstone and siltstone are strongly dominated by quartz grains. Other important constitutents are rock fragments, matrix and cement. Feldspar is rare and ranges from zero to nine percent. Most samples, however, contain only trace amounts of feldspar. The realative abundance of feldspar types is orthoclase > Na-plagioclase > microcline. Mica flakes are rare and are present in trace amounts in only a few samples.

The quartz grains are mainly monocrystalline, non-undulose, and are generally well sorted with intermediate degrees of rounding. The matrix is almost exclusively authigenic clay. X-ray diffraction indicates that kaolinite is the dominant clay mineral. Lesser amounts of illite and montmorillonite are also present. Optical evidence of chlorite was also noted. However, chlorite is present in too small amounts for detection by X-ray techniques. The clay matrix is considered to be post-depositional because it is not present at grain contacts but does fill interstices between grains. Rock fragments are chert and MRF's, which average 2.04 and 1.55 percent of these samples, respectively. Sedimentary rock fragments are absent from most sandstone and siltstone samples. Silica is the main chemical cement, usually as quartz overgrowths. However, it is present in only minor amounts, and compared to the matrix it is not a significant bonding agent. For this reason the Dakota sandstone is usually friable. Porosity for this suite of samples ranges from 0.5 percent to 22 percent. The average porosity is 10.6 percent. Figure 17 is a ternary diagram for these rocks. Fifty percent are quartzarenites. The remaining samples are sublitharenites and subarkoses. Eighty percent of these samples contain more than ninety percent quartz.

Quartz

Each thin section was examined for different quartz types. Quartz grains are classified as non-undulose, undulose and polycrystalline (Blatt, 1967; Conolly, 1965). The relative abundance of the quartz types is nonundulose undulose polycrystalline. According to Folk's system (1968), most of the quartz grains are common or plutonic quartz with lesser amounts of vein quartz and stretched metamorphic quartz (polycrystalline). Generally the quartz grains contain few inclusions except for some vacuoles that may be scattered or arranged in lines across the grain.

Two types of quartz overgrowths were recognized: post-depositional quartz overgrowths and reworked quartz overgrowths. The former type is recognized by straight crystal faces. They usually do not completely fill the intersticies between grains. Wherever they do, however, they form an interlocking network of grains. Reworked overgrowths were recognized by observing nuclei of rounded quartz grains in which the overgrowths have a very irregular outline and have been "chipped" away in places down to the surface of the original grain (Folk, 1968; Pettijohn, 1957). Sometimes the

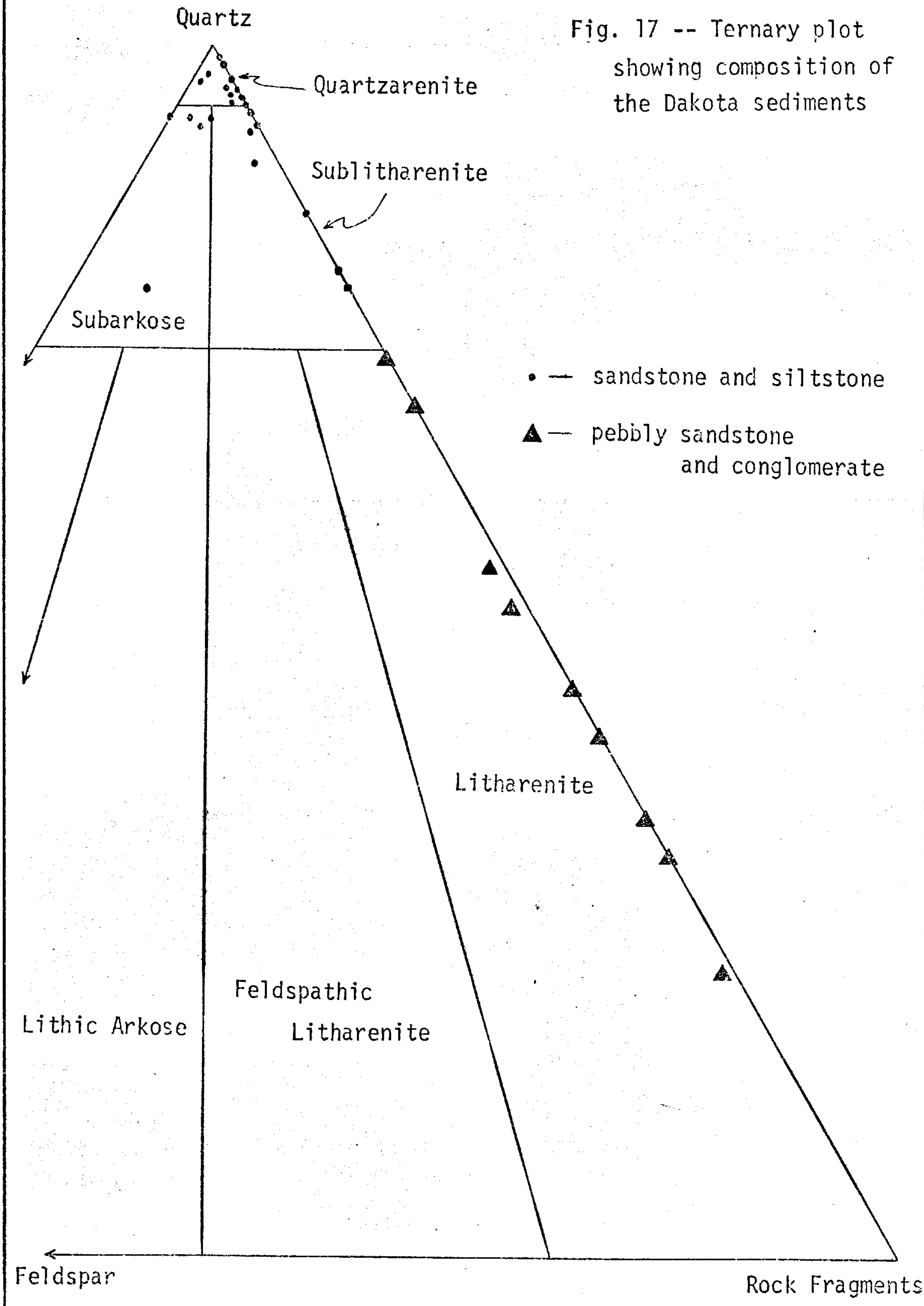


Fig. 17 -- Ternary plot showing composition of the Dakota sediments

"chipped" surfaces penetrate through the overgrowth and into the original grain.

Rock Fragments

Special attention was given to rock fragments because of their abundance in the channel lag deposits, their ubiquity in the formation in general, and their significance in determining the lithology of the source area. Two basic types of rock fragments are present: sedimentary rock fragments (SRF's) and metamorphic rock fragments (MRF's). No igneous rock fragments were noted. Specifically, SRF's are represented by the following rock types: chert, sandstone, siltstone, mudstone and claystone. The most abundant SRF's are chert, mudstone and claystone. The other types are rare. The specific rock types of MRF's could not be definitely determined because of their extremely fine-grained nature; however, they probably are either phyllite, slate or argillite.

Positive identification of microcrystalline chert versus fine-grained MRF's is difficult because of a lack of distinctive petrographic criteria (Folk, 1952). Few MRF's exhibit foliation or schistosity and rarely can other minerals such as mica flakes or feldspar be seen. Detrital quartz grains, however, are present in most MRF's. Occasionally faint evidence of preferred orientation of clay minerals is seen in the MRF's. Because of this difficulty, rock fragments from each thin section were recounted and re-examined in an attempt to establish petrographic criteria useful in distinguishing microcrystalline chert from fine-grained MRF's. The results are shown in table 5. Occasionally rock fragments were encountered

TABLE 5: Characteristics of rock fragments

	Sedimentary Rock Fragments (excluding chert)	Chert	Metamorphic Rock Fragments
Color	reddish brown	gray to dark gray	gray to black
Texture	quite variable	tends to be homogeneous with some variation in crystal size	variable (often resembles chert
Grain boundaries	extremely deformed,especially if relatively large fragment	smooth; may have very minor indentations	minor indentations to significantly deformed
Inclusions	detrital quartz grains; mica flakes	carbonate rhombs, micro-fossils, detrital quartz	detrital quartz grains mica flakes
Grain sizes	clay matrix with detrital quarts	typical chert size crystals (4-20 microns) with some larger void-filling crystals	aphanitic matrix with very fine grained to silt-sized quartz grains
Fragment Size	pebble size and smaller	pebble to very fine grained	pebble to very fine grained
Preferred orientation of matrix	often	none	occasionally
Mica	rare; where present extremely fine grained	none	rare; when present extremely fine grained
Fragment Shape	highly irregular due to compaction	similar to quartz grains or elongate	similar to quartz grains, elongate grains rare
Location	channel lag deposits	anywhere	anywhere

that could not be positively identified as either chert or MRF as described in table 5. This indicates the table's limited accuracy and shows that some of the characteristics can apply to both rock types.

Petrographic Comparisons of Sandstone and Siltstone

Limited petrographic differences are present among sandstone and siltstone deposited in the large meandering stream systems, in alluvial plain stream systems, and in overbank areas. The most obvious petrographic differences are even present in sandstone that was deposited in different parts of the large meandering streams under different flow conditions.

Figure 18 is a classification diagram of sandstone and siltstone from the large meandering stream system, the alluvial plain stream system, and the overbank deposits. All of the sandstone from the large meandering stream system is quartzarenite and sublitharenite. One of the alluvial plain sandstone is a subarkose, the other is a quartzarenite. Three of the four overbank sandstones are subarkose in composition. The fourth one is on the border between subarkose and sublitharenite. The overbank sandstone is the only type that contains a significant amount of feldspar.

Figure 19 is a grains-matrix-cement ternary plot of the same sandstone and siltstone shown in figure 18. No clear grouping can be seen from this comparison.

To clarify further petrographic comparisons of the three groups of sandstones and stilstones, those of the large meandering stream system are discussed separately. Those of the alluvial plain

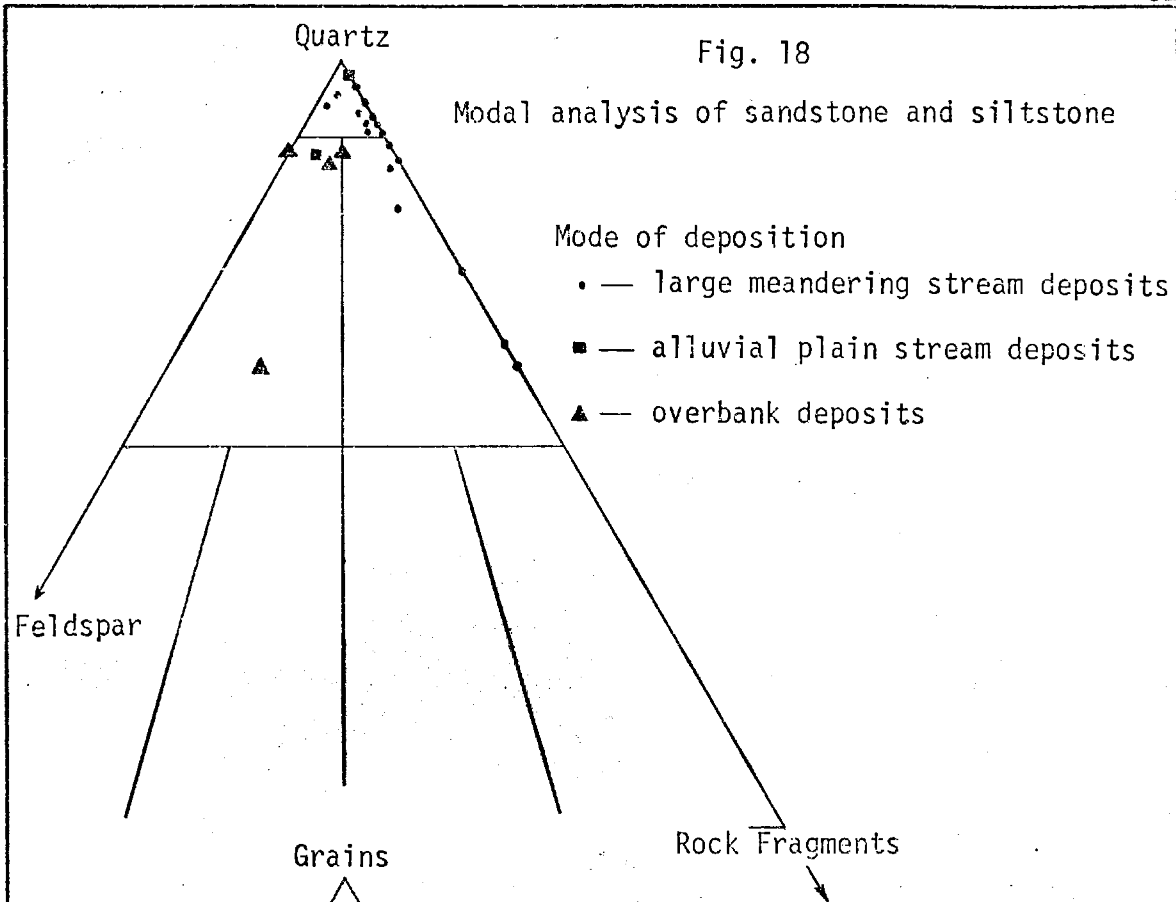


Fig. 18

Modal analysis of sandstone and siltstone

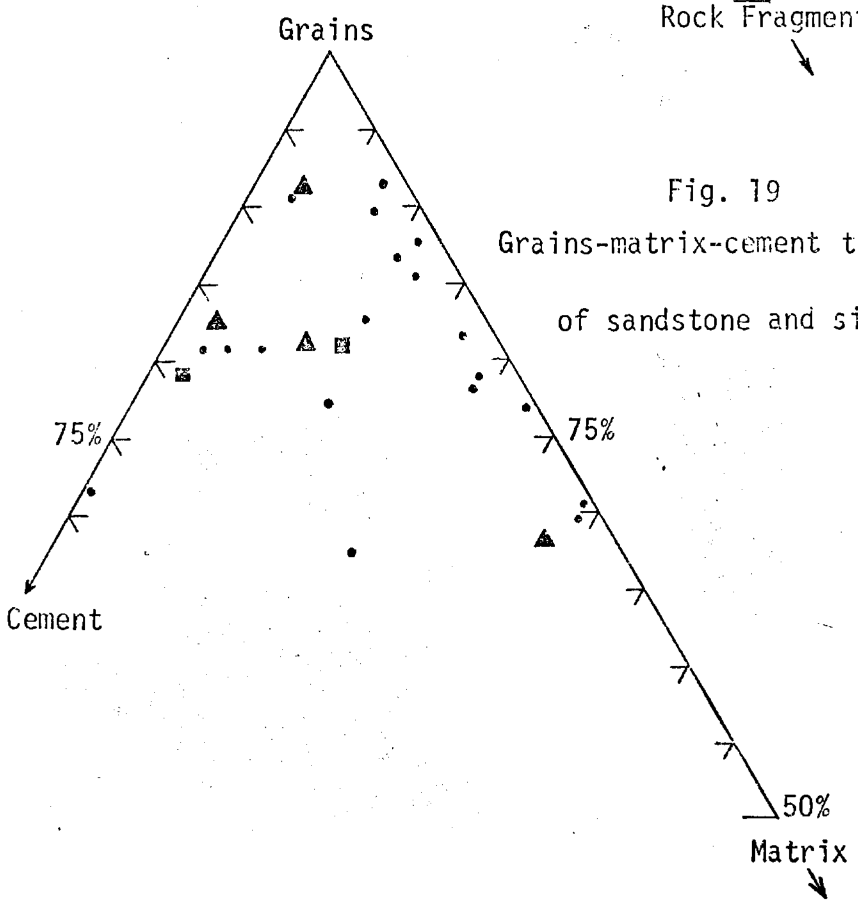


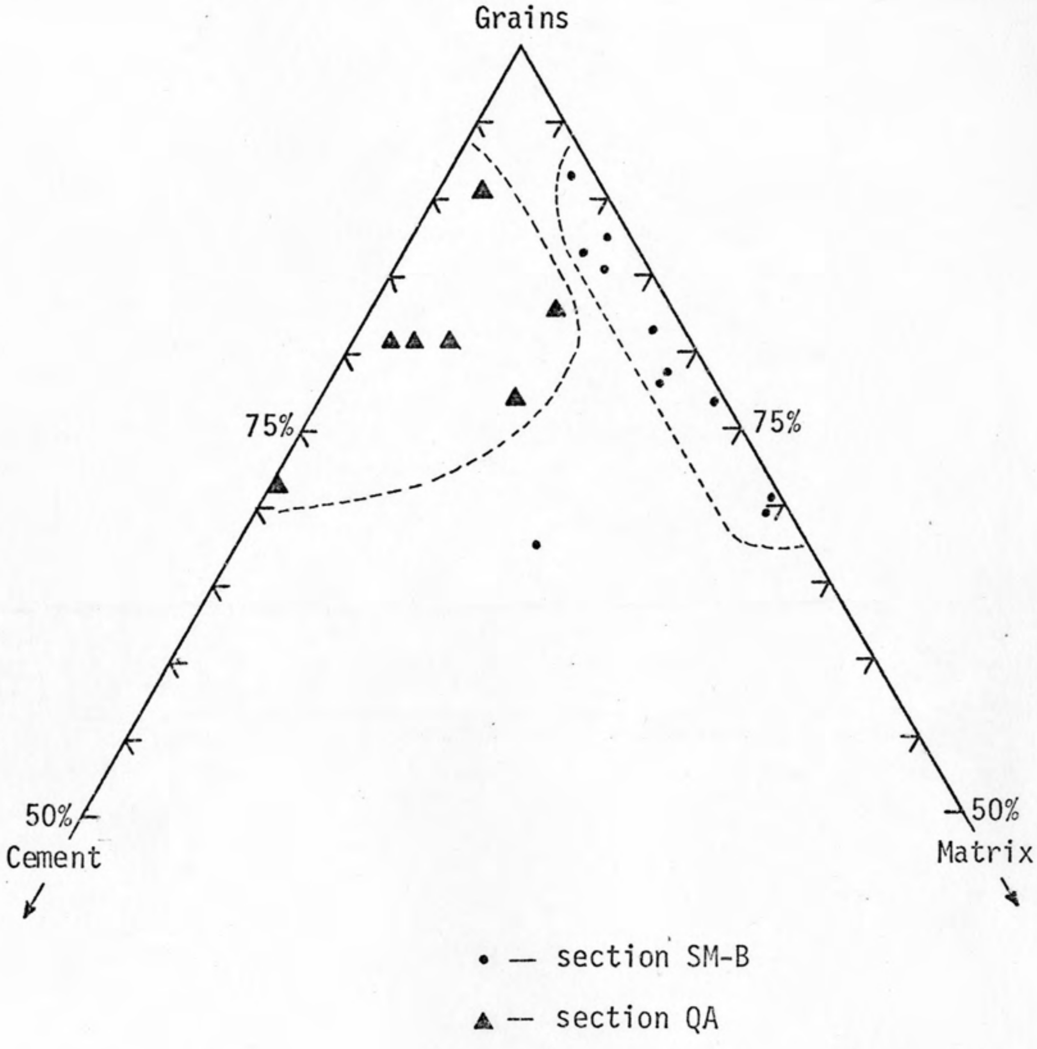
Fig. 19

Grains-matrix-cement ternary plot

of sandstone and siltstone

stream system and the overbank deposits are discussed together. The same type of comparisons are made for all three groups, which are modeled after studies by Picard, 1971; Picard and High, 1970, 1972.

Pronounced petrographic variations were noted in sandstone that was deposited in different flow conditions within the large meandering stream system. This is best demonstrated by comparing samples of sections QA and SM-B. Section SM-B represents deposition in the main stream channel as indicated by trough and planar cross-stratification, point bar deposits and its relatively large thickness (112 feet). Section QA represents deposition at or near bank full conditions as indicated by abundant horizontal stratification, its high stratigraphic position relative to the main channel, and its relative thinness (67 feet). Figure 20 is a grain-matrix-cement plot of the samples from these two sections. The percent grains is about the same in both cases. The main difference is in the precent of cement and matrix. QA samples contain more cement and less matrix than SM-B samples. Even though sections QA and SM-B are not part of the same channel, they probably are indicative of petrographic changes within the large meandering stream deposits. The differences in the matrix content imply that at least some of the matrix is detrital and that lesser amounts of it are deposited in sections similar to QA because of higher velocity flow conditions. There also is an inverse relationship between the contents of matrix and cement. SM-B samples have relatively high matrix percentages and low cement percentages. QA sandstones have relatively low matrix percentages and high cement percentages. Figure 21 further illustrates the matrix-cement relationship for QA and SM-B sandstones. The



Grains - matrix - cement ternary plot of samples from large meandering stream deposits

Fig. 20

Scatter Plot of Authigenic Cement Versus Matrix

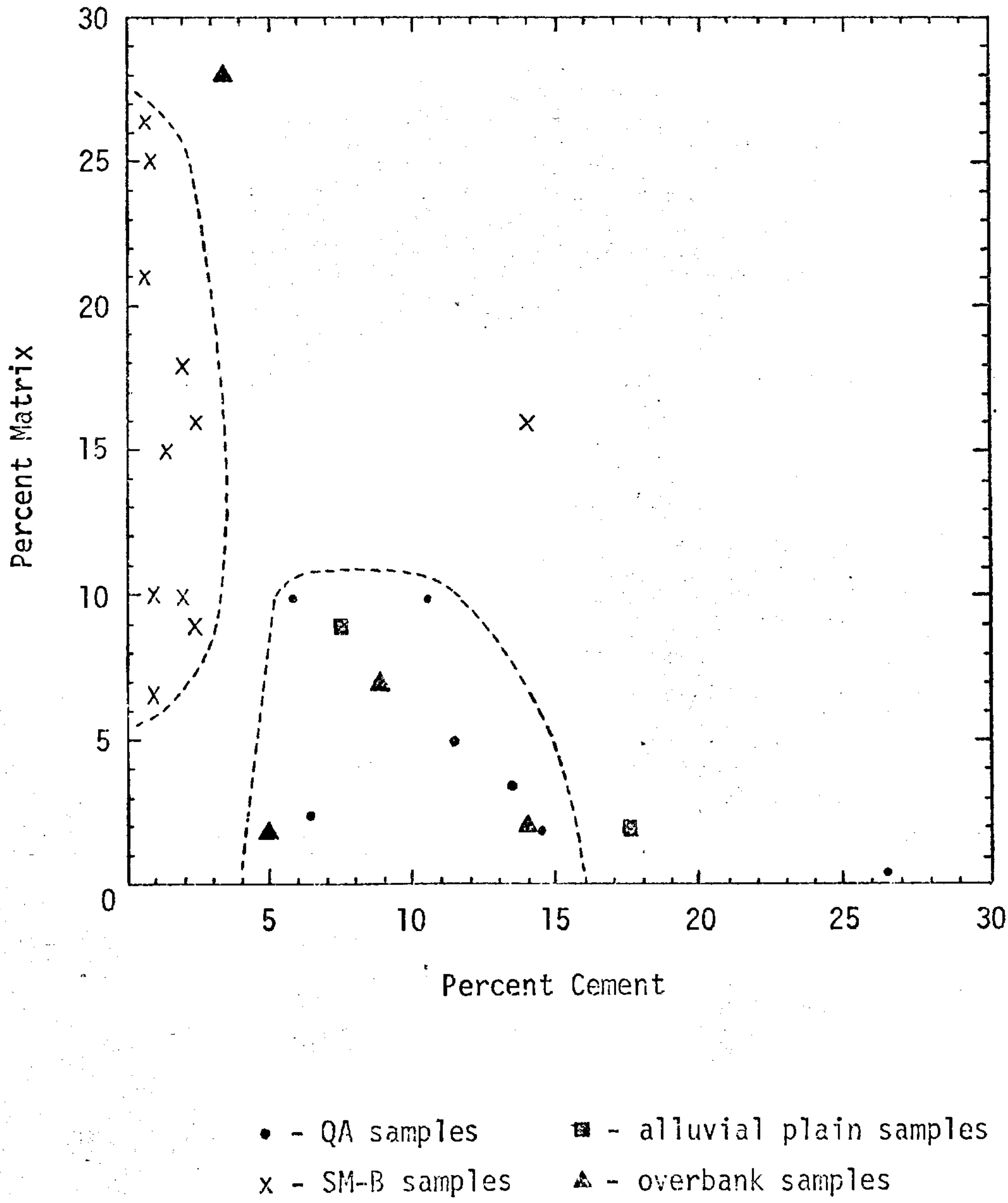


Fig. 21

dotted lines demonstrate the graphical separation of these two groups. Note that samples from the other two groups plot in the same area of the graph as QA. Figures 22 and 23 show the relationship of matrix and cement to quartz for these same deposits. In each case the two groups, QA and SM-B, cluster well graphically, as shown by the dotted lines.

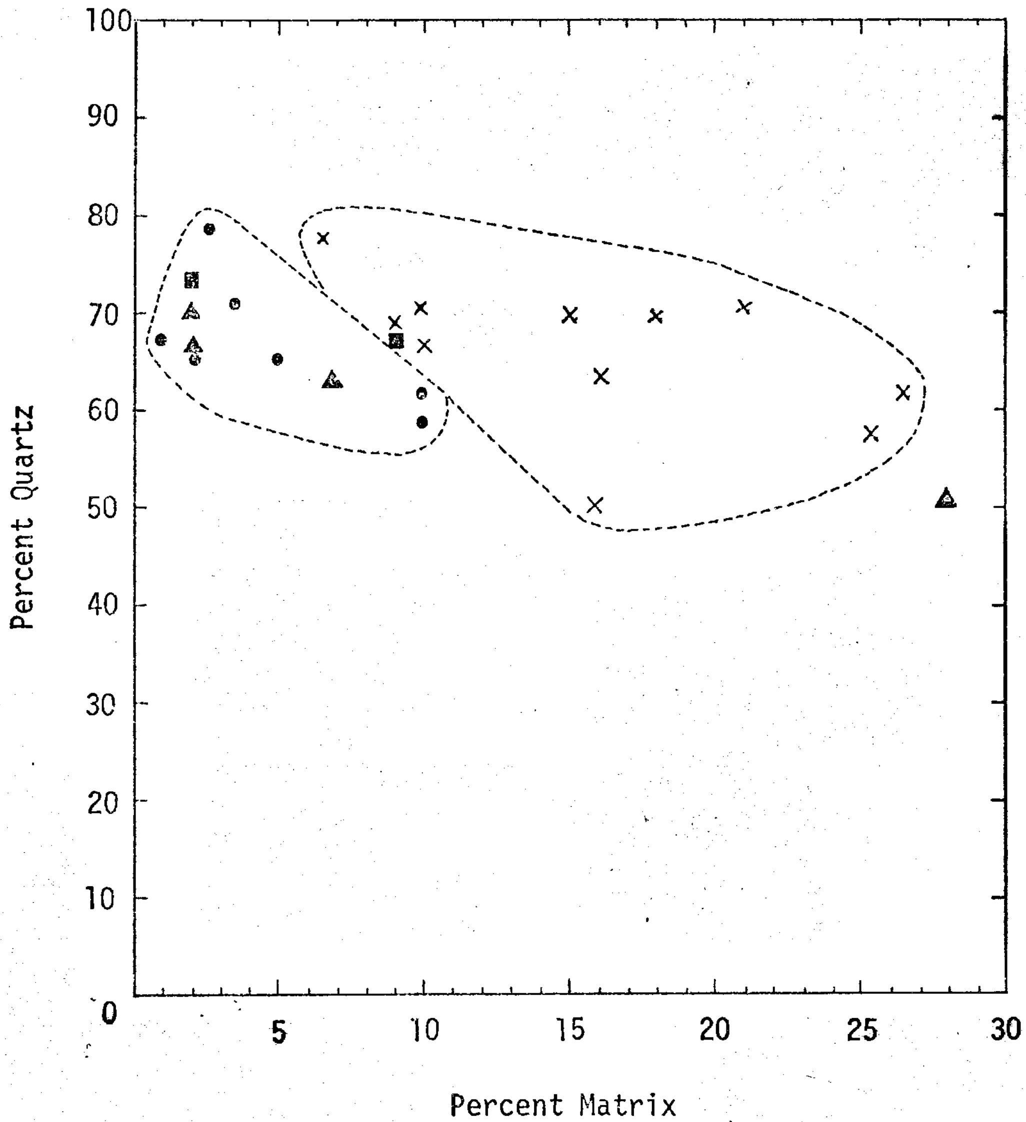
The same petrographic comparisons that were made of sections QA and SM-B were applied to sandstone of alluvial plain stream deposits and overbank deposits. Alluvial plain stream deposits are represented by sections DC and C. Overbank deposits are represented by section GM. Petrographically, these two groups of sandstone are similar to each other as shown in figures 21, 22 and 23. Therefore, it would appear to be difficult to distinguish them petrographically. Also, these petrographic comparisons show that sandstone from the alluvial plain stream system and overbank areas resembles sandstone of section QA.

In summary, it appears that petrographic analysis is not a strong indicator of the different modes of fluvial deposition that have been discussed. All the sandstone and siltstone is similar petrographically except for sandstone deposited in or near the main channel of the large meandering streams as represented by section SM-B.

Diagenesis

The principle diagenetic effect on the Dakota sediments is the formation of clay minerals. They form most of the matrix material and are the primary bonding agent of the coarse-grained facies.

Scatter Plot of Quartz Versus Matrix



● - QA samples ■ - alluvial plain samples

x - SM-B samples ▲ - overbank samples

Fig. 22

Scatter Plot of Quartz Versus Cement

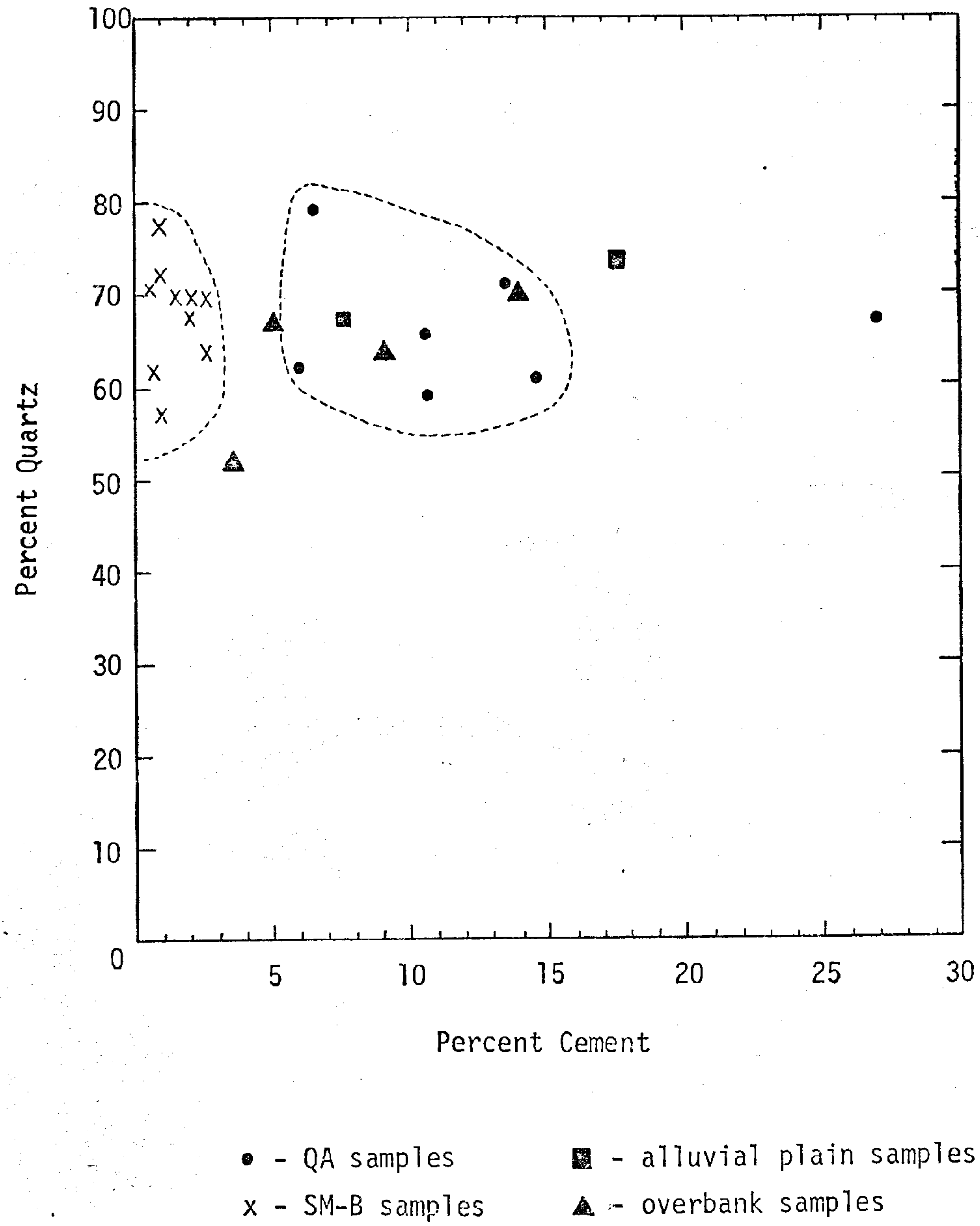


Fig. 23

Kaolinite is the most abundant clay mineral. Lesser amounts of illite, montmorillonite and chlorite are also present. Thin-section examination precludes the origin of the clays from the alteration of original constitutents. Such an origin could account for only a minor portion of the authigenic material because feldspar and mica are the only minerals in the coarse-grained facies that could alter into clay minerals, and they are present only in trace amounts (Carrigy and Mellon, 1964). From thin-sections it was determined that the authigenic clays must have been derived from another source. The most likely source is from water that was expelled from the overlying Mowry Formation. These waters must have moved through the interstices of the Dakota sediments and precipitated the clay minerals. The silica cement probably originated from the Mowry as well. Chronologically, precipitation of the silica preceded that of the clays.

It should be noted that fresh samples are difficult to obtain. It is likely that fresh samples contain less kaolinite and more carbonate cement than the weathered samples (Potter and Glass, 1958, p. 35-43). Carbonate cement is almost non-existent in the weathered samples.

PALEOCURRENTS

Paleocurrent directions were determined from sedimentary structures at each measured section. A total of 349 measurements were made, mainly from small- and medium-scale trough and planar cross-stratification. The number of measurements at each locality ranged from 10 to 64 and averaged 34.9 per locality. Paleocurrent measurements were corrected for tectonic tilt whenever the formation dipped over 15 degrees (Potter and Pettijohn, 1963, p. 260).

Methods

Paleocurrent data was processed in two different ways. First, the data was evaluated in terms of modal vectors as described by Tanner (1959). This method was slightly modified by dividing a compass diagram into twelve 30 degree arcs instead of eight 45 degree arcs. This method established the modal direction of sediment transport for various groups of data. However, since most of the paleocurrent measurements were essentially unimodal, a more informative method (Potter and Pettijohn, 1963, p. 264) of analyzing the data was used. The calculations for grouped data of this latter method are

$$V = \sum_{i=1}^{n} n_i \cos x_i$$

$$W = \sum_{i=1}^{n} n_i \sin x_i$$

$$\overline{X} = \arctan W/V$$

$$R = (V^2 + W^2)^{1/2}$$

$$L = (R/n)100$$

where $\bar{x}$ is the azimuth of the resultant vector (vector mean), R is the magnitude of the vector mean, and L is the magnitude of the vector mean in terms of percent. L is a measure of the concentration of the azimuths; the greater the L the greater the concentration. For the purposes of this thesis, the important figures are $\bar{x}$ and L. The appropriate calculations were made with the following three objectives:

a) to quantitatively evaluate paleocurrent measurement data of ancient meandering stream deposits,

b) to compare the results of a) to the results of the ancient alluvial plain stream deposits, and

c) to determine the net regional dispersal direction of the Dakota sediments.

These objectives were approached by calculating $\bar{x}$ and L for each cycle of the meandering stream deposits. This established the direction of sediment movement and the concentration of azimuths in the channel portion of each cycle. Secondly, at each outcrop the variation of $\bar{x}$ of each channel was observed. This shows the amount of change in the direction of stream flow through time at that outcrop. Thirdly, $\bar{x}$ and L were computed from the paleocurrent data of all the cycles at each outcrop. From this calculation, $\bar{x}$ indicates the net direction of sediment movement at each outcrop through time, whereas L indicates the vertical consistency of paleocurrent directions at each outcrop through time. Finally, all of the paleocurrent measurements of the study area were combined and computed for $\bar{x}$, which is the goal of objective c).

Results

The results of the computations are listed in table 6. Concerning objectives a) and b), the concentration of azimuths (L) in the channels of the large meandering stream deposits average about 73.2 percent. The outcrops, as a whole, have an L of about 44.5 percent. The same comparisons for the ancient alluvial plain stream deposits are 61.2 percent and 37.7 percent respectively. Data concerning the third objective was obtained by computing $\bar{x}$ from the total number of paleocurrent measurements (349) that were taken in the study area. In this case $\bar{x}$ was oriented N2.7^{o}E. Figure 24 shows the vertical variation of $\bar{x}$ at the outcrop. Figure 25 shows the net direction of sediment movement at each studied locality; figure 26 shows the net regional dispersal direction of the Dakota sediments.

Interpretation

The results of the paleocurrent calculations indicate that paleocurrent azimuths of the ancient meandering channel deposits of the Dakota are not widely dispersed, but fairly well concentrated as shown by the 73.2 percent average of L. The combined total L of all the cycles of each outcrop, which averages 44.5 percent, indicates that the direction of flow changed substantially through time, which is indicated in figure 24. The variable patterns are expected from sinuous streams. Comparison of the results of paleocurrent calculations show that $\bar{x}$ and L are similar in both stream systems. This suggests that alluvial plain streams were also meandering.

TABLE 6: Paleocurrent azimuth concentration (L) of Dakota stream deposits

Location

(Large meandering stream deposits)

		SM-A	SM-B	SM-C	SM-D	QA	S	M
Fluvial Cycles	6		66.0%(13)					
	5					99.0%(6)	79.7%(13)	
	4		91.7%(10)		73.3%(8)	66.5%(6)	70.8%(7)	
	3		74.5%(15)	99.8%(4)	98.9%(3)	99.7%(6)	99.4%(7)	97.0%(4)
	2	96.2%(7)	48.0%(11)	36.5%(20)	63.3%(12)	70.9%(7)	22.1%(9)	45.3%(7)
	1	97.6%(15)	72.2%(15)	41.0%(8)	57.7%(12)	42.4%(14)	20.2%(20)	96.0%(3)
Combined Total		36.3%(22)	38.1%(64)	2.2%(32)	36.1%(35)	68.3%(39)	38.9%(56)	91.3%(14)

L averages 73.2% for individual cycles; combined totals for each location average 44.5%

(Alluvial plain stream deposits)

		DC	C
Fluvial Cycles	4		75.4%(13)
	3		20.1%(22)
	2		93.8%(12)
	1	32.4%(10)	84.4%(13)
Combined Total		32.4%(10)	43.0%(60)

L averages 61.2% for individual cycles; combined totals for each location average 37.7%

CYCLIC VARIATION OF $\overline{X}$

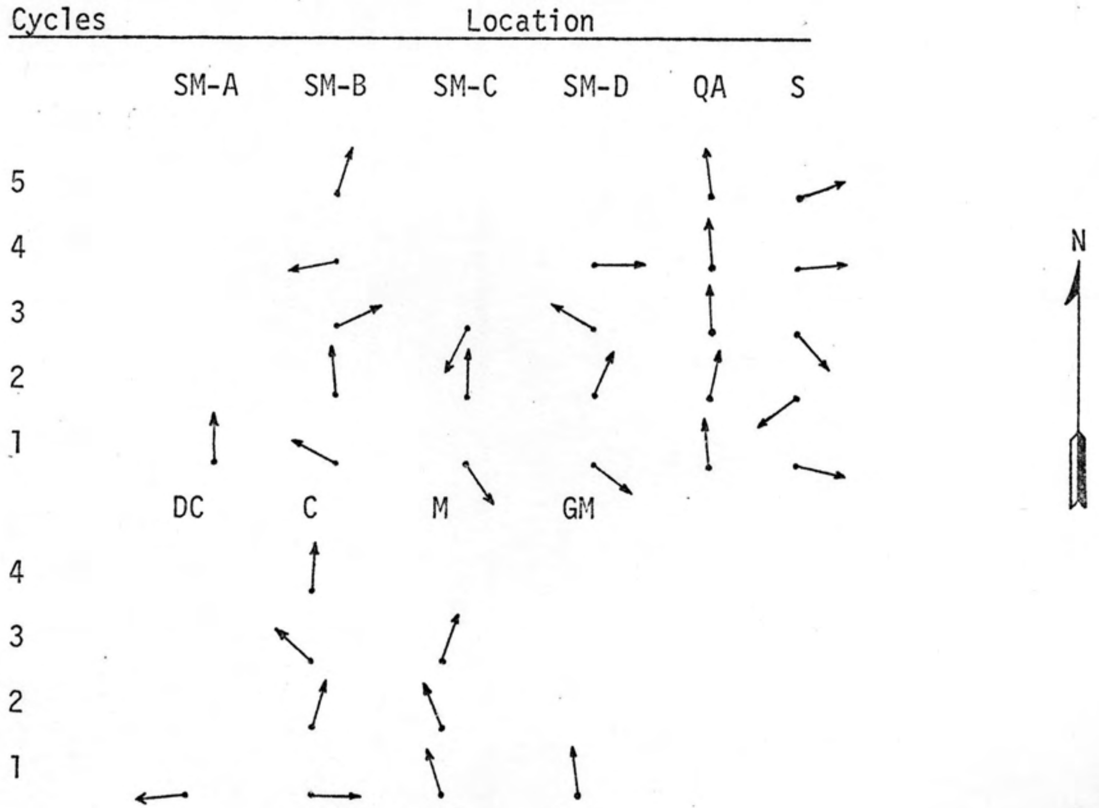


Fig. 24

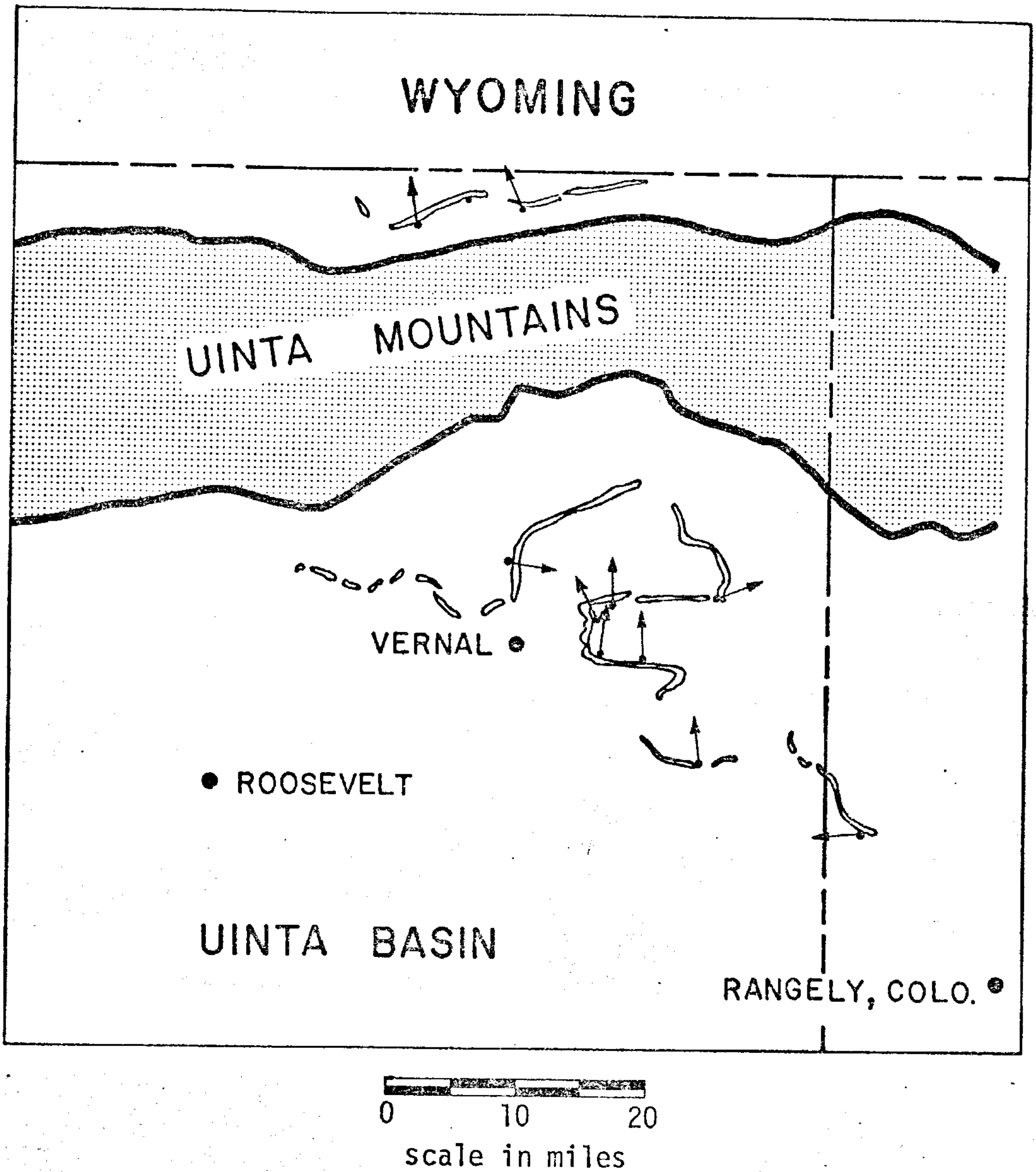
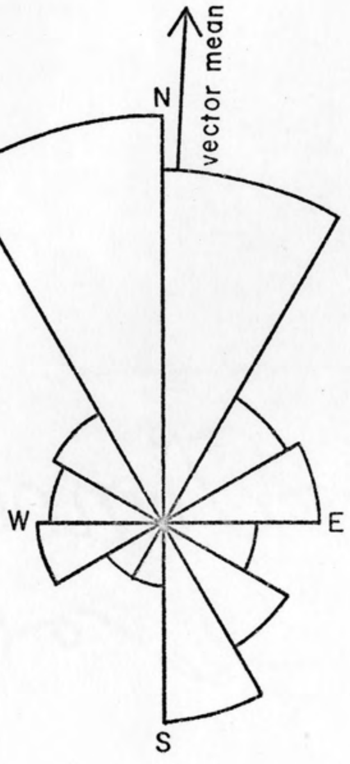


Fig. 25 --Shows net direction of sediment movement at each locality

NET REGIONAL PALEOCURRENT DISPERSION PATTERN



N = 349

$\bar{x}$ = N 2.7° E

L = 27.3 %

Fig. 26

"COARSE - GRAINED UNIT"

Description

The "coarse-grained unit" is a dark reddish-brown pebbly sandstone and conglomerate (figure 27). It is usually situated at the top of the Dakota in direct contact with the Mowry Formation. It is present at every locality except GM and QA. Its thickness ranges from 0 to 40 feet. This unit is poorly sorted with randomly distributed granules and pebbles. Generally, it is structureless except at a few localities. The structures that were observed were studied in an effort to determine the origin of this unit. The structures studied are small-scale ripples in sandstone, large-scale ripples in conglomerate and medium-scale troughs in pebbly sandstone and conglomerate.

Ripple indices were determined for a total of 21 ripple sets from four different locations as described by Tanner (1967). Determinations of ripple index (RI) were limited to five sets because reliable ripple height measurements could not always be made. RI values obtained are 11.7, 6.3, 6.0, 5.2 and 3.3. Corresponding ripple symmetry index (RSI) values are 2.0, 1.3, 1.6, 1.3, and 2.3. RSI values for the remaining 16 ripple sets range from 1.3 to 6.4. The five ripple sets in which RI versus RSI values can be compared suggest that they are wave-form ripples (Tanner, 1967). RSI values for the other 16 cases suggest that they are both current- and

Fig. 27 --Exposure of "coarse-grained unit" at section SM-B. It is the upper-most unit that is slightly more resistant to erosion than the underlying fluvial sandstone.

wave-formed ripples. Several values of the latter case fall in the indeterminate range for RSI (1.5-4.0), but based on association, other origins are unlikely.

According to Tanner (1967) genetic interpretations of RSI values not in the indeterminate range have a confidence level of 98 percent. Therefore, the interpretation of the 16 ripple sets in which RSI values only were determined is considered quite reliable. The genetic interpretation of 3 of the 5 sets in which RI and RSI values were made is more suspect. These ripples, contrary to the others, are large-scale. Wavelengths range from 26 inches to 5 feet. Ripple height varies from 5 inches to 18 inches. The lithology is pebbly sandstone and conglomerate. As previously stated, the ripple indices indicate wave-form origin. This is debatable because of the ripple magnitude and the coarse-grained lithology. Also the ripple indices and corresponding origins, as determined by Tanner, are presumably for sand-size material only. These large-scale ripples are only found in outcrops of the large meandering stream deposits and apparently only in topographically low areas of the upper surface.

PROVENANCE

From the paleocurrent data, it was determined that the general direction of sediment dispersal was to the north; hence, the source area probably was somewhere on the south. The most likely source area was in west-central and southern Utah and adjacent portions of eastern Nevada (MacKenzie and Ryan, 1962, p. 44-61; and Young, 1970, p. 147-159). This region was occupied by the Mesocordilleran Geanticline, a highland area from which the dispersal system transported sediments north and east into Colorado and Wyoming.

In general, the source area was dominated by sedimentary rocks. Erosion of prexisting sandstone and limestone was responsible for most of the Dakota sediments. Metamorphic source terrains contributed minor amounts of material. The specific types of metamorphic source rocks could not be determined although most MRF's are extremely fine-grained, probably phyllite, slate or argillite. Rare large fragments of quartzite were noted.

Abundant petrographic criteria indicate an older sedimentary source. All the sandstone of the Dakota is quartz-rich and contains little, if any, labile constitutents. All are quartzarenite or quartz-rich varities of sublitharenite or subarkose. Feldspars usually are present only in trace amounts. Quartz types are mixed but nonundulose, plutonic quartz is dominant. Many quartz grains apparently are reworked because some have good overgrowths and others do not. Also the nuclei of the overgrown grains usually are well rounded.

Chert is ubiquitous in the Dakota and is one of the most diagnostic features of a sedimentary source terrain. It is generally more abundant than MRF's. Pebbly sandstone and conglomerate is common and is indicative of a sedimentary source. Metamorphic source rocks were evidently present as indicated by MRF's. Virtually all MRF's are extremely fine-grained. Occasionally a quartzite fragment was observed in the channel lag deposits. It is conceivable, however, that the MRF's are actually very resistant detrital fragments reworked from prexisting clastic sediments.

Many textural features also indicate sedimentary source rocks. The Dakota is characterized by fairly well rounded quartz grains, which suggests that they have been recycled. A high degree of rounding of the heavy minerals in the Dakota also indicates more than one episode of erosion and transportation. Textural inversions are not common but are present. The types of textural inversions observed were a) fairly well rounded grains that were not well sorted, and b) well-sorted bimodal sediments. These inversion types probably represent multiple sedimentary source rocks (Folk, 1968, p. 106).

DISPERSAL SYSTEM

The dispersal system of the Dakota sediments was probably a complex fluvial system characterized by meandering streams throughout. This system evolved through three stages of stream development; each represented by characteristic deposits. The three stages are graphically depicted in figure 28.

As previously discussed, two basic types of streams were present during Dakota time; the relatively large meandering streams and the smaller alluvial plain streams. Paleocurrent information indicates that alluvial plain streams were meandering as well. The large meandering streams evolved through two stages of development. Stage I, the earliest, is characterized by streams that apparently were quite large as indicated by the thickness of their deposits. The lower boundary surface is undulating because of scouring action into the Cedar Mountain Formation. Stage I streams, therefore, are degrading streams as indicated by their downward erosion. The banks were probably cohesive enough to minimize the amount of lateral migration, which allowed time for substantial quantities of overbank material to accumulate and be preserved. Topography, therefore, probably gained enough relief to further inhibit channel migration. Lateral movement was not totally eliminated, however.

Stage II streams represent significant changes in the dispersal system. These were meandering streams that were somewhat smaller than those of Stage I. The lower boundary is not undulatory but is smooth

Stage III

Small, alluvial plain streams

Stage II

stage I

Large, meandering streams

(somewhat smaller than Stage I)

Stage I

Large, meandering streams

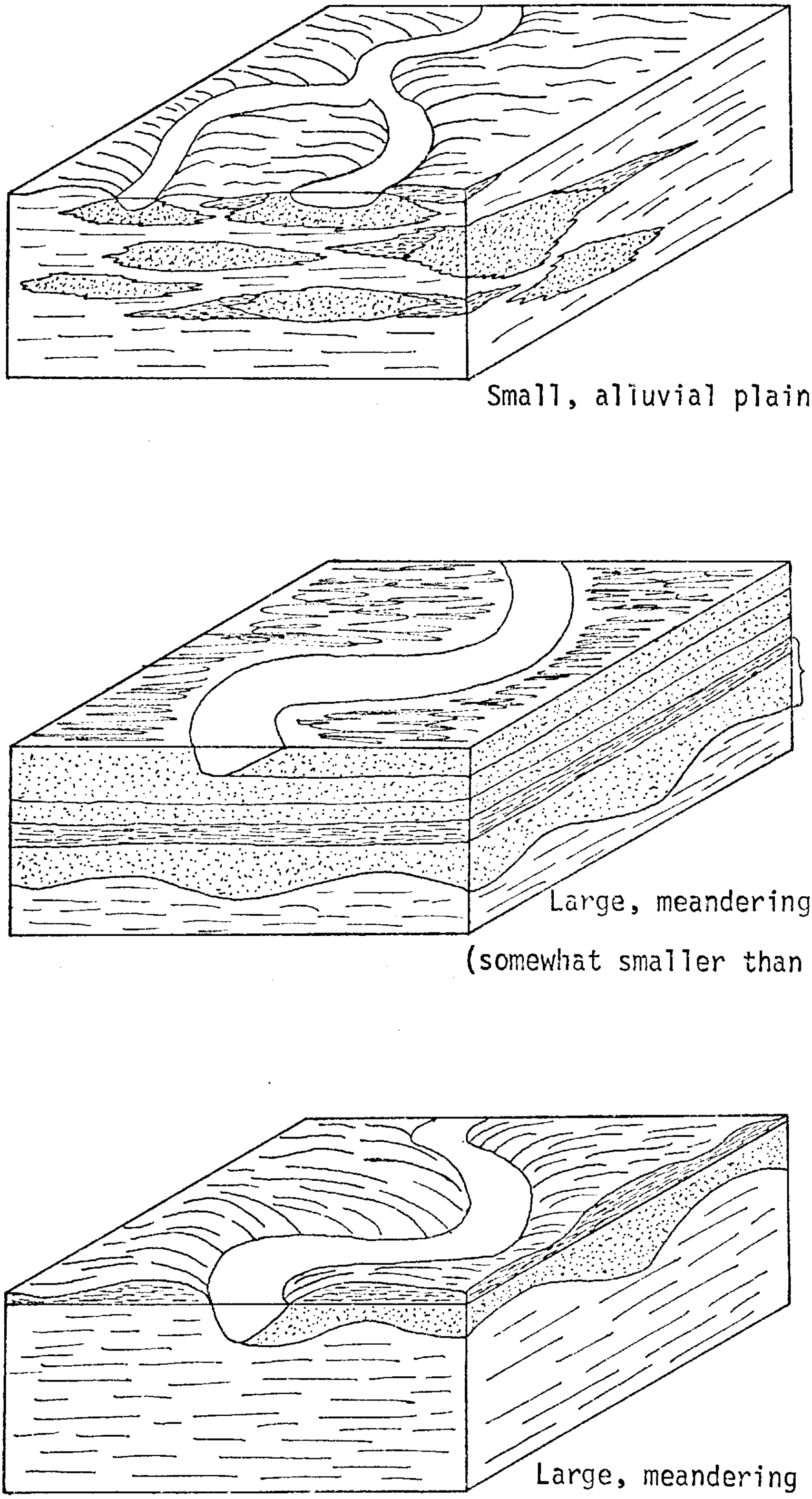


Fig. 28

and horizontal. This suggests that the streams of Stage II had approached "grade" and reach equilibrium with the surroundings. Lateral migration of the streams is suggested, whereas downward erosion was probably negligible. The banks of the streams apparently were not resistant to lateral erosion, which allowed the streams to migrate rapidly back-and forth across the floodplain. This accelerated rate of lateral movement did not time for substantial thicknesses of overbank material to accumulate on the floodplain. Frequent reworking of the floodplain prevented such material from being preserved and probably produced a flat topography.

These two stages of stream development have produced a sequence of sediments that represent "filling-up" of the depositional basin. Stage I streams were in disequilibrium with the tectonic and (or) climatic setting. These streams then evolved into Stage II streams that represent continued filling of the basin under graded conditions. All outcrops of the large meandering stream deposits show both stages of stream development.

The third type of stream development, Stage III, is represented by the alluvial plain stream system. Stage III streams were definitely formed after those of Stage I and probably simultaneously with those of Stage II. This relationship was determined from the outcrop at section M near Manila, Utah. At this location Stage III stream deposits overlie Stage I stream deposits. Also, Stage III stream deposits are in contact with the Mowry Shale as are those of Stage II. Individual channel deposits of Stage III are arranged in an en echelon manner separated by overbank material. In Stage III deposits were found the only example of crevasse-splay deposits. The en enchelon arrangement is interpreted to represent shifting of the channels into nearby topographic low areas. Stage III probably is an aggrading system. Except for section M, outcrops of Stage III deposits are exclusive of deposits of other stages.

All of the sandstone bodies of the dispersal system are elongate bodies. The specific type is difficult to determine from surface exposures; but, probably, dendroid and ribbon varieties are all present (Potter, 1962). Elongate sand bodies are usually oriented perpendicular to the depositional strike and parallel with the paleoslope.

DEPOSITIONAL ENVIRONMENTS

The Dakota Formation within the study area was deposited in a fluvial environment. This was determined by observing the erosional surface at the lower contact and by studying the sedimentary structures, textural parameters, petrography and paleocurrents. Subenvironments were recognized as channel and overbank deposition. Each forms a lithologic facies within the Dakota. Specific types of stream deposits include channel lag, point bar, levee and possible crevasse-splay deposits.

As previously discussed, the three types of streams represent the channel facies of the fluvial environment. The nature of these streams, as indicated by their deposits, in conjunction with the transgressive Mowry sea suggest that the best large-scale model of the depositional environment is a low-lying plain, probably near the sea, on which sluggish meandering streams flowed. Deposits of Stage I streams were more distant from the sea than those of Stage II and State III. This is because Stage I deposits are oldest and that the Mowry directly overlies Stages II and III.

The mode of origin of the "coarse-grained unit" is less certain. It is conceivable that it could have formed in either a fluvial environment or some transitional environment between continental or marine conditions such as an estuary, tidal flat or a river that is strongly affected by tidal currents. It could be argued that a swiftly flowing stream would be necessary to transport such coarse-grained material. The medium-scale troughs plus this unit's close association with the fluvial rocks of the Dakota support the fluvial hypothesis. Evidence in favor of deposition in one of the transitional environments is its widespread occurrence, which makes correlation possible over much of the study area. Also, in spite of the debatable origin of the large-scale ripples, they appear likely to have formed in strong, bimodally opposed currents. The reason for this is that coarse-grained ripples that have originated in unidirectional fluvial conditions appear to have long wave-lengths, much longer than the wavelength observed in the "coarse-grained unit" (Thiel, 1932). The contact between the "coarse-grained unit" and the underlying fluvial deposits is probably unconformable. The writer favors the interpretation of the "coarse-grained unit" as representing a transitional environment. It is therefore felt that the "coarse-grained unit" is genetically related to the transgression of the Mowry sea and is therefore not part of the Dakota Formation depositional environment.

CONCLUSIONS

In conclusion, the Dakota Formation in northeastern Utah is a continental fluvial deposit. It is characterized by two different lithologic facies; a coarse-grained channel facies and a fine-grained overbank facies. The channel facies is represented by two types of outcrops that indicate a change in the dispersal system. Lateral accretion is responsible for virtually all of the deposition in the channel facies. Most of the channel deposition is in the form of point bars. Also, the channel facies is characterized by cycles, each representing a single episode of fluvial deposition.

Certain textural parameters, expecially grain size, are valuable in indentifying the type of stream in which the sediments were deposited. Petrographic studies showed that the coarse-grained channel facies is quartz-rich. Matrix and rock fragments are the other main constituents. Detailed paleocurrent analysis demonstrated that all of the Dakota streams were meandering. Paleocurrent azimuths are fairly well concentrated for single channels but less concentrated for the outcrop as a whole. The regional dispersal direction is almost due north.

The "coarse-grained unit", present at the top of the channel facies, is thought to have originated in a transitional environment between continental and marine conditions as a product of the transgressing Mowry sea. From these conclusions, a new upper contact is proposed and it lies at the base of the "coarse-grained unit."

The provenance area for the Dakota sediments was probably in south-central Utah and adjacent portions of Nevada. The source terrane consisted of older sedimentary rocks and lesser amounts of fine-grained metamorphic rocks.

The dispersal system was composed of three different forms of streams. The differences in the streams were in size, degree of lateral migration, presence or absence of overbank deposits and equilibrium or disequilibrium conditions with the geologic and (or) climatic setting.

The dominant environment of deposition was probably variable in terms of distance from the sea. Stage I streams were probably at a greater distance from the sea than streams of Stages II and III. The environment of deposition for Stage I deposits is concluded to be a fairly large stream valley at an undetermined distance from the sea. Stages II and III represent deposition on a low-lying alluvial plain nearer to the sea, probably a coastal plain. The ultimate site of deposition by Dakota streams was probably north of the study area in western Wyoming.

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